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Aging of the Lumbar Vertebrae Using Known Age and Sex Samples

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AGING OF THE LUMBAR VERTEBRAE USING KNOWN AGE AND SEX SAMPLES

by

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Under the Direction of Frank L'Engle Williams

ABSTRACT

The dimensions of the lumbar vertebrae are examined in order to determine if these measurements can be used to predict the age of an individual, and if the lumbar vertebrae exhibit sexual dimorphism. Various statistical techniques were utilized to analyze several dimensions of the lumbar vertebrae. Aging patterns in the lumbar elements are distinct between males and females, and females exhibit compression of the L3 element, which may be related to vertebral wedging. Some dimensions of the lumbar vertebrae are sexually dimorphic.

INDEX WORDS: Lumbar lordosis, Human life history, Skeletal aging, Growth patterns, Sexual dimorphism

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1 INTRODUCTION

The vertebral column of humans is unique among the animal species in both function and aging patterns. Humans are one of only a few species that engage in bipedal locomotive behavior, and the only species that uses bipedalism exclusively. Consequently, the vertebral column has evolved in humans to be a weight bearing structure, and in turn the human vertebral column exhibits distinct aging patterns (Whitcome et al. 2007: 1075). Additionally, bipedal locomotion may have also encouraged the development of sexually dimorphic traits in the vertebral column due to the increased lordosis of pregnant human females that is not found in their quadrapedal counterparts (Whitcome et al. 2007: 1075). The purpose of this study is to explore the changes in vertebral dimension throughout the human lifecycle, and to determine the degree of sexual dimorphism exhibited by the lumbar spine.

The vertebrae are exceedingly important structures in forensic and archaeological settings. They are often one of the only surviving bones from archaeological sites (Hussein et al. 2008: 616), and because of their importance as a weight-bearing organ in the human body, vertebrae often provide a plethora of information about an individual or population's living condition (Hussein et al. 2008: 613). Vertebrae can provide information about diet, congenital anomalies, degenerative and infectious diseases, trauma, and malignancies (Hussein et al. 2008: 613, Schmorl and Junghanns 1971: 116 – 117). Due to the variety of information that can be gathered from the vertebral elements, understanding the aging patterns and the degree of sexual dimorphism of the vertebrae could be of critical importance for both archaeologists and forensic anthropologists.

This thesis, as previously stated, will focus on the aging and sex differences of the vertebrae, specifically the lumbar vertebrae. The lumbar region is of particular interest because

these vertebrae support the more weight than the cervical and thoracic elements. The first section of this thesis will discuss the ontogeny of the vertebrae, and current literature on the topic of vertebral aging and sexual dimorphism. The proceeding sections will elaborate on the theory behind vertebral aging and human life expectancies, overview the process of skeletal aging throughout the human life cycle, and present original research on the topic of vertebral aging and sexual dimorphism.

1.1 Vertebral Development and Degeneration

The vertebral column is composed of thirty-three bony segments that can be broken down into five distinct regions: the cervical vertebrae, the thoracic vertebrae, the lumbar vertebrae, the sacrum, and the coccyx (Steele and Bramblett 1988: 111). Of these regions, the cervical, thoracic, and lumbar vertebrae can be distinguished from the sacrum and coccyx on the basis of mobility, and consequently, the true vertebral column is composed of the mobile segments: the cervical, the thoracic, and the lumbar vertebrae (Steele and Bramblett 1988: 111 - 115). Each segment of the vertebral column grows, develops, and degenerates at different rates, and the development and degeneration of the vertebral column is inextricably linked to bipedal locomotion that characterizes the human species.

The formation of the vertebral column *in utero* can be divided into three stages (Widjaja et al. 2006: 554). The first stage of vertebral development, known as membranous development, begins around the third week of gestation (Widjaja et al. 2006: 554). During this period, two parallel columns of mesodermal cells form segments that are divided by fissures (Widjaja et al. 2006: 554). Each segment of mesoderm, known as somite, can be divided into medial and lateral portions (Widjaja et al. 2006: 554). The medial portion, known as the sclerotome, develops into the vertebrae as gestation continues, and the lateral portion develops into muscles and skin

(Scheuer and Black 2000: 188, Widjaja et al. 2006: 554). The second stage of vertebral development is known as chondrification, in which densely packed cells in the inferior portion of the sclerotome migrate cranially to form intervertebral discs and the remaining cells in the inferior portion of each sclerotome form the precursor to the vertebral body (Scheuer and Black 2000: 190 – 191, Widjaja et al. 2006: 554). During the sixth week of gestation, two chondrification centers appear on each primordial vertebra, and cells at these centers migrate toward one another and fuse together, forming the cartilaginous centrum of each vertebral body (Scheuer and Black 2000: 191, Widjaja et al. 2006: 554). Around the fourth fetal month, the cartilaginous neural arches of each vertebrae fuse together at the spinous process, producing individual cartilaginous elements (Scheuer and Black 2000: 191). Ossification of the vertebral bodies is characteristic of the final stage of vertebral development (Scheuer and Black 2000: 192, Widjaja et al. 2006: 556). At the end of the second intrauterine month, ossification centers form on the neural arch and centrum, and at birth, cartilage connects three bony components of each vertebra (Widjaja et al. 2006: 556).

Three primary centers of ossification appear in the atlas (C1) around the seventh fetal week (Scheuer and Black 2000: 198). The centers are located at each of the lateral masses and directly posterior to what will eventually become the superior articular facets (Scheuer and Black 2000: 198). After birth, spinal maturation exhibits a general pattern of increasing rate of development from the two ends of the vertebral column, both cranially and caudally, towards the thoracic vertebrae (Bramblett and Steele 1988: 132). Of the cervical vertebrae, both the atlas (C1) and the axis (C2) have distinctive patterns of maturation and development. At birth, the atlas is composed of two bony segments (Bramblett and Steele 1988: 117, Scheuer and Black 2000: 198). Between one and two years of age, the cartilaginous anterior arch develops one to

several centers of ossification, and by three – four years of age, the anterior arch can be identified as a separate unit of the atlas (Bramblett and Steele 1988: 117, Scheuer and Black 2000: 198 - 199). The anterior arch closes around the fifth or sixth year of age, and the posterior arch fuses completely by four to five years (Scheuer and Black 2000: 199). The atlas becomes close to its final adult size around age six (Bramblett and Steele 1988: 117, Scheuer and Black 2000: 199).

The axis (C2) forms five primary ossification sites *in utero*: two at the neural arch, one at the true centrum of the axis, and one for each half of the main body of the dens (Scheuer and Black 2000: 200). The ossification centers for the neural arches appear around seven to eight weeks of intrauterine development (Bramblett and Steele 1988: 119, Scheuer and Black 2000: 201). The centrum of the axis ossifies between the fourth and fifth month *in utero*, and at around the seventh to the eighth months *in utero*, the intradental synchondrosis, which eventually forms the body of the dens, fuses together (Scheuer and Black 2000: 201). At birth, four separate bones represent the axis: the dens, the centrum, and two longer bones that will eventually form the neural arch (Bramblett and Steele 1988: 119, Scheuer and Black 2000: 201). Around two years of age, the ossiculum terminale, the small portion of bone that becomes the superior most portion of the apex of the dens, begins to ossify and is completely fused to the dens around ten to twelve years of age (Scheuer and Black 2000: 202). Complete fusion for the intradental synchondrosis and posterior synchondrosis occurs around three to four years of age (Scheuer and Black 2000: 201). Also, between third and fifth years of age, the transverse foramina are fully formed on the axis (Scheuer and Black 2000: 202). The complete fusion of the axis occurs around the ages of four to six years, though in some individuals, the odontoid never completely fuses with the rest of the axis (Bramblett and Steele 1988: 119, Scheuer and Black 2000: 202). The inferior surface

of the centrum fuses completely with the epiphyseal plate around nineteen to twenty years of age (Steele and Bramblett 1988: 119).

The third through seventh cervical vertebrae develop three centers of ossification *in utero*: one for each of the neural arches and one for the centrum (Scheuer and Black 2000: 203). The neural arches fuse prior to the centrum, and ossification for the centra progresses from C7 to C3, where the ossification of the C7 centrum occurs around the beginning of the third month *in utero*, and the ossification of the C3 vertebrae begins towards the beginning of the fourth intrauterine month (Scheuer and Black 2000: 203). At birth, each cervical vertebra is represented by two neural arches and one centrum. The neural arches fuse with the centrum proceeding from C3 caudally between the ages of four and six years (Steele and Bramblett 1988: 116). Epiphyses appear on the inferior and superior parts of the cervical bodies around 17 years of age, and they completely fuse around 25 years of age (Steele and Bramblett 1988: 116).

The thoracic vertebrae follow an ossification schedule similar to that of the cervical. Around the eighth week of intrauterine development, two ossification centers associated with the neural arches form in the first two thoracic vertebrae, and by the tenth week, each thoracic vertebra possess these centers of ossification (Scheuer and Black 2000: 205). Ossification centers appear for the centra around week nine of interuterine development, and each vertebra possesses this ossification center by the end of week 10 (Scheuer and Black 2000: 205). The costal elements elongate to form ribs, and they begin to ossify around the eighth to ninth week of fetal development independent of the thoracic vertebrae (Scheuer and Black 2000: 205). At birth, the thoracic vertebrae are represented by three bony elements, and within the first year of life through the second year, the neural arches of the thoracic vertebrae fuse together (Scheuer and Black 2000: 206). Around four to five years of age, the laminae fuse with the centrum (Steele

and Bramblett 1988: 120, Scheuer and Black 2000: 206). The secondary epiphyses for the transverse and spinous processes appear around the 12 to 16 (Scheuer and Black 2000: 209), and unite completely by the age of 18 (Steele and Bramblett 1988: 120 - 121). The epiphyseal ring on the centrum begins to form before 17 years of age, and fuses completely by age 25 (Steele and Bramblett 1988: 121).

The lumbar vertebrae develop similarly to the rest of the true vertebrae, with the exception of the atlas and axis. Ossification of the centra of most cranial vertebrae occurs around week 9 to 10 *in utero*, and progresses towards the fifth lumbar by the end of the third month of pregnancy (Scheuer and Black 2000: 206). The neural arches begin to ossify *in utero* slightly later than the centra, starting with the upper lumbar vertebrae around the 11th week of *in utero* development and progressing to L5 by the end of the fourth fetal month (Scheuer and Black 2000: 206). Similarly to the cervical and thoracic vertebrae, the lumbar vertebrae are represented by three bony masses at birth. The arches fuse together for the four cranial lumbar vertebrae around the end of the first year, but may remain unfused in L5 for until four years of age (Scheuer and Black 2000: 206). The arches fuse to the centrum around the sixth year of life (Steele and Bramblett 1988: 125). The lumbar transverse processes begin to form around the end of the first year of life (Scheuer and Black 2000: 206). Secondary epiphyses appear during puberty for the lumbar vertebrae, and fusion is complete before the age of 18 years (Steele and Bramblett 1988: 125). The epiphyseal ring appears around the ages of 12 to 16 and completely fuses after the 18 years (Scheuer and Black 2000: 209, Steele and Bramblett 1988: 125).

During puberty, secondary epiphyses appear for all vertebral elements and typically are completely fused by adulthood (Scheuer and Black 2000: 209, Steele and Bramblett 1988: 125). Secondary epiphyses are also known as secondary centers of ossification, and they typically

appear and begin to fuse after growth of the vertebrae is complete (Scheuer and Black 2000: 208). The typical pattern of fusion begins at the cranial cervical vertebrae and caudal lumbar vertebrae, and progresses in both directions towards the thoracic segment (Steele and Bramblett 1988: 132 - 133). The number of secondary epiphyses varies based on type of vertebra. Typical cervical vertebrae have six epiphyses: one for each transverse process, one for each tip of the spinous process, an inferior ring and a superior ring on the surface of the centrum (Scheuer and Black 2000: 210 - 211). Thoracic vertebrae typically have five epiphyses: one for each transverse process, one for the spinous process, and the superior and inferior rings on the body (Scheuer and Black 2000: 211). The lumbar vertebrae typically exhibit seven epiphyses: one for each transverse process, one for each mamillary process, one for the spinous process and one ring per inferior and superior portion of the centrum (Scheuer and Black 2000: 213). Unlike the pattern observed in the ossification of the lumbar vertebrae, the secondary epiphyses appear earlier for L5, and appearance progresses cranially over time towards L1 (Scheuer and Black 2000: 213). This pattern is true for all the secondary epiphyses, including the epiphyseal rings on the superior and inferior aspects of the centrum (Scheuer and Black 2000: 213).

The development of the sacrum is more complex than that of the other vertebral elements (Steele and Bramblett 1988: 128). Although the number of ossification centers varies between individuals, there are 14 centers of ossification that are found consistently on the sacrum (Scheuer and Black 2000: 206 – 207). Two annular rings for each of the five sacral elements represent 10 of the 14 centers (Scheuer and Black 2000: 206). The other four consist of two auricular surface epiphyses and two more epiphyses for the lateral margins of the sacrum (Scheuer and Black 2000: 206). Several other smaller centers of ossification exist on the sacrum as well, specifically on the processes of the medial sacral crest and the transverse processes

(Scheuer and Black 2000: 206). Epiphyseal fusion for most epiphyses on the sacrum begins around age 16 – 17 years, and S3, S4, and S5 fuse together around the age of 22 – 23 (Steele and Bramblett 1988: 129). The second element of the sacrum, S2 fuses with S3 around the age of 23 – 24, and S1 fuses with S2 around the age of 30 – 32 (Steele and Bramblett 1988: 129). The coccyx does not exhibit a regular pattern of ossification and fusion. During adulthood, the coccyx is composed of the first segment (caudal 1) and the three fused inferior segments (Steele and Bramblett 1988: 130). In older adults, the first element of the coccyx fuses with the sacrum, though this occurs more in females than in males (Steele and Bramblett 1988: 130). In some cases, the entire coccyx will fuse together (Steele and Bramblett 1988: 130).

Around the age of 25, the spinal column is completely developed, and thereafter, the spinal elements begin a progressive degeneration process that accelerates around the age of 50 (Steele and Bramblett 1988: 133). As the epiphyseal ring forms on the superior and inferior aspects of each vertebral element, striations form on each centrum, but as adulthood progresses, the striations slowly erode away due to the constant reconfiguring and regeneration of the bone (Steele and Bramblett 1988: 132 - 133). For the lower thoracic elements, striation loss occurs progressively from age 23, but the lumbar vertebrae can retain striations up to the age of 50 (Steele and Bramblett 1988: 133). During later stages of adulthood, the same process that causes the obliteration of the striations also causes the epiphyseal ring on the surface of the centrum to degenerate until there is little distinction between the surface of the body and the ring (Steele and Bramblett 1988: 133). After the age of 50, the degeneration of the spinal column accelerates with the increasing appearance of osteophytes, lipping, and macroporosity (Steele and Bramblett 1988: 133). Osteophytosis occurs when the surface of the vertebra becomes irregular and bony projections riddle its surface. Osteoarthritis, or lipping, can also develop on the articular surfaces

of the vertebra (Steel and Bramblett 1988: 133 - 135). Osteophytosis can lead to ankylosing spondylitis after young adulthood, which may restrict movement until the end of life (Schmorl and Junghanns 1971: 187 - 189, Steele and Bramblett 1988: 135). Schmorl's nodes, which are caused by the compressive forces of the vertebrae on the intervertebral discs, also become more prevalent with increasing age (Schmorl and Junghanns 1971: 159). As the superior vertebral body compresses the intervertebral disc, any weak points on the inferior vertebral body may collapse, and the intervertebral disc tissue may protrude into the vertebral body, resulting in the formation of a Schmorl's node (Hussein et al. 2009: 620, Schmorl and Junghanns 1971: 159).

1.2 Sexual Dimorphism

Sexual dimorphism in the lumbar spine is likely due to a combination of several different factors, including bipedal locomotive behavior. Bipedalism causes a dramatic shift on the length and curvature of the spine (Whitcome et al. 2007: 1075). Elongation of the lumbar region of the spine is one trait that humans have evolved in order to accommodate bipedal locomotion, and the lumbar region must exhibit posterior concavity, also known as lordosis, in order to stabilize the body and maintain equilibrium while standing upright (Whitcome et al. 2007: 1075). Quadrupeds do not exhibit lordosis of the lumbar region because their arms stabilize their bodies while moving (Whitcome et al. 2007: 1075). One might expect lordosis to be correlated with an increase in osteoporosis or osteoarthritis in the lumbar region, but no significant increase in occurrence of degenerative disorders and degree of lumbar lordosis has been found (Papadakis et al. 2009: 611) However, lordosis does affect the shape of the vertebral body in females, who exhibit greater lordosis of the spine due to fetal loading during pregnancy (Whitcome et al. 2007: 1076).

1.3 Literature Review

Only a handful of authors have focused their research on the growth and development of the vertebral elements. Mary Frances Ericksen (1976: 575 - 580, 1978a: 241 - 246, 1978b: 247 - 250) published a series of three articles focusing on aspects of aging in L1 – L5 from the mid to late 1970's. She studied age-related aspects of the lumbar vertebrae from the Terry collection at the Smithsonian Institute (Ericksen 1976: 575). She calculated the height-breadth index, biconcavity index, average biconcavity index, the anterior-posterior height index, and the flaring index for each vertebra, and distinguished individuals on the basis of race (black and white) and sex (Ericksen 1976: 577). Her research concluded that there is a statistically significant negative correlation between height-breadth indices of lumbar vertebrae, and that there is a negative correlation with flaring index and age, but this correlation is not statistically significant with the exception of the height-breadth index in all of the vertebral elements (Ericksen 1976: 578, 1978a: 242 - 244, 1978b: 247). Also, the flaring index in the L5 of black males and white females exhibited a significant correlation with age (Ericksen 1978b: 247). The main distinction between Ericksen's research and this study is the statistical methods utilized. Ericksen's (1976: 575) studies utilized linear regression modeling in order to determine if the relationships between age and vertebral indices are significant, whereas this study will focus more on ANOVA to determine if age and vertebral dimensions are significantly correlated with one another. Essentially, Ericksen (1976: 575), by using linear regression modeling, is asking whether the vertebral indices she calculated can be used to predict age, whereas in this study, the ANOVA will reveal the validity of biological age groups in regards to various vertebral dimensions.

Widjaja et al. (2005: 553) conducted a study using postmortem MRI on 30 fetuses ranging from 14 to 40 gestational weeks. The purpose of the study was to understand the normal

appearance of the fetal spine with MRI imaging so that abnormalities could be accurately assessed. Age was estimated from the fetuses they analyzed based on the woman's last menstrual cycle and the sonography from 20 weeks after the last menstrual cycle. Each fetus was autopsied in order to ensure the absence of structural abnormalities in the spinal column that may have been the cause of death (Widjaja et al. 2005: 553). The researchers found that the fetal spine develops at a specific rate, and they were able to establish specific developmental stages for the growth of the spine *in utero* (Widjaja et al. 2005: 554). Additionally, they conclude that the vertebrae exhibit a linear growth pattern *in utero* (Widjaja et al. 2005: 559).

Rühli et al. (2005: 460) studied fourteen dimensions of the vertebrae to determine if there is a link between changes in these dimensions and age. They conducted this study with two skeletal populations: a historic population comprised of 277 skeletons that range from the Late Upper Paleolithic to the Late Medieval period, and a modern population comprised of 71 skeletons that range from the mid-19th century to the early 20th century (Rühli et al. 2005: 461). They measured these dimensions on the C3, C7, T1, T6, T10, L1, and L5 vertebrae, and estimated age using anthropological aging methods, though the specific aging techniques used were not discussed. Once all of the measurements were collected, they used SPSS 11.0 and Excel 2000 to calculate their results, using multiple linear regression analysis, similar to Ericksen's (1976: 575) research, to determine whether a statistically significant link between age and the changes in these dimensions existed (Rühli et al. 2005: 462). They found that in males, several of the dimensions exhibited a significant correlation with age (Rühli et al. 2005: 463). Females, however, did not exhibit a single significant relationship between age and vertebral shape.

In addition to the previously mentioned articles, researchers in the field of orthodontics have also published several articles on the aging of the spine. Cervical development is

specifically useful for the field of orthodontics in that it may produce a viable indicator of skeletal maturity during puberty, which is necessary for finding the optimal time to correct mandibular deficiencies (Wong et al. 2009: 484.e1). The optimal time for growth modification is typically during the peak of pubertal growth, and for many years, radiographic analysis of the wrists have been the best indicators of skeletal maturity for orthodontists (Wong et al. 2009: 484.e1). However, research into using cervical vertebrae to determine skeletal maturity has yielded positive results for this field, and, considering that radiographs of the head are already necessary, this method of assessing skeletal maturity is advantageous because it reduces patients' exposure to radiation (Chatzigianni et al 2009: 481.e1 – 481.e9, Chen et al. 2008: 720.e1 – 720.e7, Hassel and Farman 1995: 58 - 66, Román et al. 2002: 303 - 311, Uysal et al. 2006: 622 - 628).

2 THEORY

Life history theory is a key component to understanding why the lumbar region of the spine develops and degenerates at the observed rate. The spine begins to degenerate around the age of 50 in humans, which means that the degeneration process of the vertebrae can last upwards of half the maximum lifespan of humans (Steele and Bramblett 1988: 133). Also, it should be noted that the degeneration of the skeleton itself occurs around the age of 50, which is also around the time that reproductive cessation occurs in women (Steele and Bramblett 1988: 133, 164, 228; Leigh and Blomquist 2007: 397). Due to this extended period of longevity, humans exhibit an extremely long period of skeletal degeneration. The question now comes to mind: why exactly do humans exhibit such a long life history?

2.1 Life History Theory

Several theories currently exist today to explain the variation in the life history of animals, specifically humans. One such model takes a somewhat simplistic view of the diversity of life history among animal species. This model, known as r- and K- selection, divides animals into two groups; animals that are selected for increased population growth, or r- selection, and animals that are selected for their carrying capacity, or K-selection (Hawkes 2006a: 51). Under this model, r-selecting animals tend to mature at shorter intervals and produce large numbers of offspring and K-selecting animals mature at a slower rate and produce fewer offspring, but also invest more into the offspring they do produce (Hawkes 2006a: 51). This model, though worth mentioning, does not stand up well to empirical testing since several species do not correlate well with this continuum (Hawkes 2006a: 52, Stearns 1977: 155).

Charnov's life history invariants model is one theory that is used to explain the patterns in life history across species (Hawkes 2006a). Charnov (1993:viii) studied multiple aspects of the

life history of several vertebrate species, such as age of senescence and interbirth interval, and discovered that these dimensions are consistently correlated with one another within higher taxonomic groupings (birds, fish, mammals) when each parameter is converted into dimensionless numbers. Essentially, he found that despite the actual difference between the life history features of animals within the same higher taxonomic grouping, animals within this grouping exhibited the same ratios, or invariants, when comparing these life history features. In other words, the correlations among certain life history events are conserved between species of the same higher taxonomic category. Charnov's invariants play an important role in the theoretical basis for both the grandmother hypothesis and the embodied capital hypothesis (Hawkes 2006b: 106, Kaplan et al. 2000: 157 -158).

Several theorists have used the concept of trade-offs to interpret the differences between animals that experience short life histories and animals that experience long life histories (Hawkes 2006b: 98 - 99). The trade-off faced by animal species is between using energy to either invest in growing larger, or to invest in reproduction (Hawkes 2006b: 98 - 99). Limited time and energy in this finite world are the main causes of the need to make a choice between growth and reproduction among species (Hawkes 2006b: 98 - 99). Energy spent on growth and development means less energy for reproduction, and vice versa (Hawkes 2006b: 98 - 99). This inevitably means that larger animals exhibit longer life histories compared to animals that invested less time in growth in order to reproduce sooner (Hawkes 2006b: 98 - 99). However, as Hawkes points out, large body size may be the cause of increased longevity instead of the other way around (2006b: 100). A high mortality risk would restrict the time allotted for growth and development, selecting for a smaller body size and faster maturity to compensate for the increased likelihood of death (Hawkes 2006b: 100). A low mortality risk would have the

opposite effect, allowing for a larger body size. A larger body size also correlates with larger offspring produced, longer gestation lengths, and reduced annual fecundity (Hawkes 2006b: 101 - 102).

The grandmother hypothesis analyzes the existence of reproductive cessation in humans, and uses aspects of Charnov's theory to explain this phenomenon (Hawkes et al. 1997: 563). Humans experience an extremely long post-reproductive period compared to other primates (Hawkes et al. 1997: 551). Reproductive cessation in women occurs around the age of 50, which is approximately half way through the maximum lifespan of humans, whereas reproductive cessation is a rarely seen phenomenon in primates (Leigh and Blomquist 2007: 400). The grandmother hypothesis argues that the extended post-reproductive period may have conveyed an evolutionary advantage by allowing non-reproductive grandmothers to assist their reproductive daughters in caring for their children (Hawkes et al. 1997: 551). Hawkes et al. (1997: 552) explains that the contribution of grandmothers would increase the production of children by their daughters because grandmothers could provide food to both their daughters and grandchildren, decreasing the age between birth and weaning, which in turn would increase the annual fecundity of their daughters. The grandmother hypothesis is based on research conducted by Hawkes et al. (1997: 552 – 553), who studied the role that Hadza post-reproductive women play in the fitness of their daughters. However, this theory has been criticized because many cite that it only applies to human females (Fedigan and Pavelka 2007: 439). The grandmother hypothesis is in stark contrast to the embodied capital hypothesis, which seeks to explain the increased longevity of humans by analyzing the nutritional needs of a larger brain and the skills needed to develop proper hunting techniques to properly nourish those brains (Kaplan et al. 2000: 156).

The embodied capital hypothesis is based on research conducted by Kaplan et al. (2000: 156 – 183), who also studied the dietary contribution of females and males in hunter-gatherer societies. They found that the nutritional contribution of males was higher than that of females and children in the Ache, Hiwi and Hadza societies, and that children in hunter-gatherer groups are nutritionally dependent upon other individuals until they reach maturity (Kaplan et al. 2000: 160 - 161). Based on this information, they hypothesized that increased brain size created a selective pressure towards increased longevity because of the high level of knowledge required to acquire the high-quality food that people consume (Kaplan et al. 2000: 156 -157). Since the nutritional contribution of men is higher than that of the women and children, they theorized that hunting by men plays an important role in the continued reproduction of the human species (Kaplan et al. 2000: 156 - 157). They also observed that the children's nutritional contribution to the group is very low compared to the adults but that their contribution increases with age, especially in males (Kaplan et al. 2000: 160 - 161). Since the peak productivity in adult males occurs around the age of 35, the authors hypothesized that the children, especially early in life, are human capital in which the parents invest. The adults invest in their children in that they teach them skills necessary to survive, such as hunting and gathering, and these skills do require a lengthy period of time to master (Kaplan et al. 2000: 162 - 164). However, during the time they are learning, the adult's nutritional contribution far outweighs that of the children, but eventually the children will learn all of the necessary skills to become the primary nutritional providers for their group (Kaplan et al. 2000: 162 – 164).

2.2 Vertebral Aging Theory

Charnov's life history invariants are the basis for the theoretical framework of both the grandmother hypothesis and the embodied capital hypothesis (Hawkes 2006b: 106 - 107, Kaplan

et al. 2000: 163). Each theory attempts to explain the longevity of humans compared to other primates, and Charnov's invariants explain the life history of humans as existing on a slow-fast continuum that is symmetrical with other mammals. So, how do we frame this understanding of human life history in the context of the development and degeneration of the lumbar vertebrae?

Since the lumbar vertebrae tend to begin the process of degeneration around the age of 50, and human life history exhibits symmetry with the life history of other mammals, then the relatively early degeneration of the lumbar spine may be a result of evolutionary lag time in which lumbar development has not caught up with the extended life history of humans (Steele and Bramblett 1988: 133). As previously stated, this explanation is also used for the existence of menarche in females under the theory of the embodied capital hypothesis (Kaplan et al. 2000: 179). If there truly is an evolutionary lag time for the development of lumbar vertebrae, then why exactly does such a lag time exist? The most likely answer to this question is that the increase in life expectancy of humans is a recent occurrence. Paleodemographic data suggests that very few early humans lived beyond the age of 50, and that the trend toward increased life expectancy only occurred after the 18th century (Paine and Boldsen 2006: 328). This would support the idea that the long life expectancy of modern humans is a recent occurrence in human evolution, and that evolutionary lag time may be the main reason that the lumbar vertebrae begin to degenerate around the age of 50.

2.3 Lifestyle Factors

As Steele and Bramblett (1988: 133) point out, the degeneration of the vertebral spine can be greatly affected by the health of the individual. Hussien et al. (2009: 613) state, "the spine, being an important structure within the human skeleton, acts as an indicator of living conditions, dietary habits, diseases…congenital anomalies, trauma and tumors." Therefore, stress

experienced during the lifetime of an individual can greatly impact the aging markers of the vertebrae. Biomechanical stress during the lifetime can manifest as Schmorl's nodes on the body of the vertebrae (Üstündağ 2009: 697). Vertebral osteoporosis can also be caused by Cushing's disease, which is due to an increase in the secretion of adrenal glucosteroids (Schmorl and Junghanns 1971: 116 - 117). The glucosteroid hormones interfere with the functioning of the osteoblasts that continually remodel the bone of a living organism (Schmorl and Junghanns 1971: 116). Since the osteoblasts cannot properly remodel the skeleton, the bones become deficient in calcium and more flexible, resulting in shortening of the thoracic region and kyphosis, or extreme forward curvature of the spine (Schmorl and Junghanns 1971: 345, Steele and Bramblett 1988: 135). Stress can also lead to vertebral osteoporosis because stress also increases the production of glucosteroids, much like Cushing's disease (Schmorl and Junghanns 1971: 117).

Three categories can be used to describe disorders that affect the rate of aging of the spine: nutritional, pathological and occupational. These categories cover a plethora of defects and diseases that can affect the spine and accelerate the rate at which the spinal column degenerates.

The most common congenital defect that afflicts the spine is spina bifida (Steele and Bramblett 1988: 135). Spina bifidia occurs when the neural arches and spinous processes do not fully close, resulting in a lack of closure of the neural canal (Steele and Bramblett 1988: 135). Folate plays an important role in the development of the spinal column *in utero*, and folate deficiency or defective folate metabolism is linked to the occurrence of spina bifida (Jablonksi and Chaplin 2000: 62). In fact, folate metabolism is linked to other neural tube defects as well, including anencephalus (Jablonski and Chaplin 2000: 62). Vitamin D deficiency can lead to

rickets, which also affects the development of the spinal column. Osteomalacia is the term used to describe the softening of bone due to vitamin D deficiency (Schmorl and Junghanns 1971: 118 - 119). Osteomalacia can result in severe kyphosis of the spinal column due to wedging and anterior disc degeneration (Schmorl and Junghanns 1971: 118 - 119).

Several pathological infections can affect the vertebral column. Tuberculosis and syphilis are known to cause specific manifestations on the vertebral column (Schmorl and Junghanns 1971: 312 - 313). Tuberculous spondylitis, or tuberculosis of the spine, causes the afflicted vertebrae to develop abscesses and become granulated (Schmorl and Junghanns 1971: 317). The afflicted vertebrae may also shrink and collapse, causing severe spine curvature abnormalities, and also causing the healthy vertebrae to grow in height to compensate for the collapsed infected vertebrae (Schmorl and Junghanns 1971: 317 - 318). Syphilitic spondylitis exhibits a similar disease production to that of tuberculous spondylitis, though this disease is very rare compared to tuberculous spondylitis (Schmorl and Junghanns 1971: 312 - 313). Other infections of the spine include osteomylitis and actinomycoses, which may manifest in the vertebrae as abscesses, fibrous thickenings, and porotic texture of the bone (Schmorl and Junghanns 1971: 308).

Occupational pathologies can also affect the appearance and development of vertebrae. Biomechanical stress, as previously stated, can result in the development of Schmorl's nodes on the body of the vertebrae (Üstündağ 2009: 702 - 703). Additionally, arthritis of the vertebrae can manifest as lipping of the articular surfaces of the vertebrae or osteophyte formation on the body of the vertebrae (Steele and Bramblett 1988: 135 - 136).

3 SKELETAL AGING

Skeletal aging is a critical aspect of both forensic anthropology and bioarchaeology. Age-at-death determination can enable researchers to better understand the life history and life expectancies of ancient people, or can play a critical role in identifying the remains of a recently deceased individual. A variety of research has focused on uncovering the signs left behind by the deceased that are indicative of their age-at-death, and much of this research has coalesced into various skeletal aging techniques. The following sections will focus on the various methods included by researchers to accurately assess age, and how similar methods could be utilized to evaluate the age of the vertebrae.

3.1 Skeletal Aging Techniques

Several methods have been developed over the past century to accurately assess age, most of which examine both developmental and degenerative events that occur at specific times during the human life cycle. By analyzing these changes, researchers have developed several different aging methods, each of which can determine the age-at-death of an individual to a relative degree of certainty. However, often times individual aging methods alone only provide a relative age-at-death, and according to Lovejoy et al. (1985: 9), analyzing several different aging methods in congruence with one another yields a much more accurate assessment of age-at-death. Later research also confirms the validity of these results (Mensforth and Lovejoy 1985: 87 – 105, Bedford et al. 1993: 287).

Among the various methods to determine age-at-death, dental maturation, epiphyseal plate closure, and endocranial suture closure are excellent examples of maturity marker. Teeth erupt at known periods throughout the lifetime of an individual, with some variation, which is why dental maturation is a widely used method to assess age-at-death (see Table 3.1). Deciduous

Table 3.1 Deciduous and Permanent Tooth Eruption[1]

Tooth (Upper & Lower)	Age of Eruption	
di^1 & di_1	4.5 – 10.5 months	
di^2 & di_2	7.5 – 18 months	
dm^1 & dm_1	10.5 – 30 months	
dm^2 & dm_2	10.5 – 18 months	
C' & dc,	10.5 –30 months	
I^1 & I_1	♂ 5.0 – 9.0 years	♀ 5.6 – 8.7 years
I^2 & I_2	♂ 5.9 – 9.4 years	♀ 5.6 – 10.1 years
C' & C,	♂ 8.3 – 14.3 years	♀ 7.3 – 13.6 years
P^3 & P_3	♂ 7.5 – 13.7 years	♀ 7.1 – 13.0 years
P^4 & P_4	♂ 8.1 – 14.7 years	♀ 7.5 – 14.1 years
M^1 & M_1	♂ 4.6 – 7.9 years	♀ 4.3 – 7.7 years
M^2 & M_2	♂ 9.4 – 15.3 years	♀ 8.9 – 14.9 years
M^3 & M_3	♂ 16.5 – 20.5 years	♀ 16.5 – 20.5 years

teeth begin alveolar eruption as early as the age of 4.5 months, and by the age of two and a half years, most children exhibit all of their deciduous teeth (AlQahtani et al. 2010: 489 – 490; Steele and Bramblett 1988: 75). Permanent teeth can begin erupting around 5 years in boys and 5.6 years in girls, and permanent teeth continue to erupt at regular schedules until the last molars, M^3 and M_3, have erupted in the late teens to early 20's for both males and females (Steele and Bramblett 1988: 75). Beyond simply using the dental eruption schedule to age an individual, adults that exhibit fully erupted third molars can also be aged by analyzing the degree to which their teeth exhibit attrition (Miles 2000: 974; Steele and Bramblett 1988: 104). This method, developed by A.E.W. Miles (2000: 974), examined the different levels of wear on the permanent molars. The first molars erupt around age 6, followed by the second molars around age 12, and then the third molars in the late teens (Miles 2000: 974). Using this known schedule of dental eruption, Miles created a graded method to assess using the level of wear observed between the ages of 6 - 18 to project the level of wear after the age of 18 (Bramblett and Steele 1988: 104; Miles 2000: 194). One of the major criticisms of this method, however, is that attrition is

[1] Source: AlQahtani et al. 2010: 489 – 490; Steele and Bramblett 1988: 75

contingent upon diet, and individuals that consume grainer foods compared to others would exhibit higher levels of dental abrasion at younger ages (Steele and Bramblett 1988: 104).

Ectocranial suture closure and temporal bone analysis can also yield important information about the age-at-death of an individual. The basilar, sagittal, lambdoidal, and coronal sutures all exhibit specific schedules of closure that can be utilized to determine age (Steele and Bramblett 1988: 57). At birth, the occipital bone is represented by four individual pieces, and these pieces have completely fused together by the age of 6 (Meindl and Lovejoy 1985: 60 – 64; Steele and Bramblett 1988: 56 - 57). The basilar suture between the occipital and sphenoid bones begins to fuse around the age of 16 and fusion completes around age 21. The sagittal suture is approximately ¼ closed by the age of 19, ½ closed by the age of 23 – 25, and ¾ closed by the age of 29 – 31 (Steele and Bramblett 1988: 56 – 57). The lambdoidal suture is typically ¼ closed by the age of 25, and reaches ½ closure around the age of 35, but this suture typically remains partially open well into old age. The coronal suture is typically ¼ closed by the age of 23, and ½ closed by the age of 31 (Steele and Bramblett 1988: 56 – 57). Suture closure can corroborate the age of an individual in correlation with other age indicators, but for very young individuals, analysis of the tympanic ring can be used to distinguish newborns from toddlers (Weaver 1979: 263).

Developmental changes in the shape of the tympanic ring show a direct association with age (Weaver 1979: 268). Four stages of development of the tympanic ring can be derived from these changes (Weaver 1979: 268). The first stage is characterized by the absence of the tympanic ring and the presence of the petro-mastoid portion of the temporal bone. Newborns typically exhibit this stage of development. The second stage of development represents infants between the ages of 0 – 0.5 years, and the tympanic ring is typically U-shaped during this phase.

The third stage is similar to the second, except that the tympanic ring adheres more to the temporal bone, and the ends of the U-shaped tympanic ring are somewhat pinched. The fourth stage is slightly different from the third in that the tympanic ring is no longer U-shaped, and the two ends have coalesced to form the tympanic plate. The fourth stage is often represented by a larger inferior and a smaller superior foramen. The third and fourth stages of development are both found in infants between the ages of 1 and 2.5 years.

All of the bones in the appendicular skeleton exhibit specific schedules of epiphyseal plate closure that are meaningful when determining the age-at-death of an individual. In the arm, for instance, the epiphyses for the proximal humerus start to fuse around the age of 16, and are complete by the age of 24 (Steel and Bramblett 1988: 157). Table 3.2 summarizes the stages of epiphyseal plate closure for the humerus, ulna, radius, femur, tibia and fibula. By early adulthood, most of the epiphyses of the appendicular skeleton are completely fused, which makes epiphyseal fusion a useful indicator of adulthood. Epiphyseal fusion schedules are unique for each epiphysis and may differ based on the sex of the individual (Bramblett and Steele 1988: 156).

In addition to analyzing ossification schedules of an individual, a plethora of information about age can be gathered by analyzing the morphological changes of certain areas of the body, specifically those in which two bones rub against one another throughout the lifespan of an individual. The auricular surface of the pelvis and the pubic symphysis are examples of such areas in which specific morphological changes have been directly linked to age (Lovejoy et al. 1985; Meindl et al. 1985: 29). Meindl et al. (1985: 36 – 44) identified five biological stages of pubic symphysis aging that are summarized in Table 3.3. Young adults typically exhibit billowing on the surface of the pubic symphysis, which is quickly eroded away by the age of 30.

Table 3.2 Epiphyseal Fusion Schedule of Limb Bones in Males[2]

Bone	Epiphysis	Beginning	Active	Complete
Humerus	Distal	14	15 – 16	16
	Medial Epicondyle	12	15 – 16	19 – 20
	Proximal	16	19 – 20	23 – 24
Ulna	Proximal	16	17	18 – 19
	Distal	17	18 – 19	22 – 23
Radius	Proximal	14	16	18 – 19
	Distal	17	18 – 19	22 – 23
Femur	Lesser Trochanter		16 - 17	20
	Greater Trochanter		16 – 18	
	Distal		16 - 20	
	Head		14 - 19	
Tibia	Proxmial		18 - 19	
	Tuberosity	12 - 14	15 - 19	19
	Medial Mallelous			18
	Distal		15 - 18	18
Fibula	Proximal		15 - 20	18 – 20
	Distal		15 - 18	18

Around the age of 30, the ventral border of the pubic symphysis becomes more defined, which is also known as the formation of the ventral rampart (Meindl et al. 1985: 36 – 44). The ventral rampart develops and is typically compete around the end of the fourth decade of life. The surface of the pubic symphysis becomes much more grainy and dense around the age of 40, and typically degenerative changes, such as lipping, occur in this region around age 45.

Lovejoy et al. (1985: 21 – 27) extensively studied age-related changes of the auricular surface, and they have developed a sequence of eight stages of auricular surface aging that are summarized in table 3.4. Individuals in their early 20's typically exhibit well defined billows transversely oriented across the surface of the auricular surface. As the individual ages, the friction between the auricular surface of the illium and the adjacent auricular surface of the sacrum causes these billows to slowly disappear and the texture of the surface to change from granular to coarse. By the early 30's, the appearance of billows is greatly reduced, and striae

[2] Source: Steele and Bramblett 1988: 153 – 163, 219 - 225, Scheuer and Black 2000: 393

Table 3.3 Biological Stages of Pubic Symphysis Aging[3]

Stage	Age Range (Years)	Morphological Description
1: Preepiphyseal (Todd Stages I – V)	18 – 25	Symphyseal face exhibits pronounced billowing, ossific nodules are fusing, but not associated with the ventral rampart
	24 – 37	Remodeling has reduced the appearance of the billowing, two distinct demifaces are formed, ventral rampart formation is active, ossific nodules are fusing, but not associated with the rampart
2: Active Epiphyseal Phase (Todd Stage VI)	30 - 35	Active formation of the ventral rampart, symphyseal face remains uneven and granular
3: Immediate Postepiphyseal Phase (Todd Stage VII)	36 – 40	Ventral rampart formation is complete or close to completion, marked textural transition of the symphyseal face to fine grained and dense
4: Predegenerative (Todd Stage VIII)	40 – 44	Face is smooth and inactive, absence of any degenerative changes
5: Degenerative (Todd Stages IX – X)	45 – 50	Thin elevated rim begins to form on the dorsal margin of the symphysis, irregular lipping of the dorsal margin appear, pitting appears on the surface of the symphysis

begin to form on the auricular surface. By the beginning of the fourth decade, these striae have also eroded away, and the transverse organization is almost completely lost. The apex and retro-auricular surface may also become eroded and irregular during this period in life. Lipping and macroporosity may become present during the fifth decade of life, and by the sixth decade of life, the surface may become very irregular and riddled with osteophytes.

The fourth sternal rib also exhibits specific developmental and degenerative morphology that can be used to assess age similar to that of the auricular surface of the illium and the pubic symphysis (Iscan et al. 1984: 148 - 156). Iscan et al. (1984: 148 - 156) developed this aging technique by analyzing the fourth sternal rib of 93 white males. This technique assesses three features of pit development on the sternal end of the fourth rib; pit depth, pit shape, and rim and wall configuration. Each feature is scored based on six developmental stages tailored to each

[3] Source: Meindl et al. 1985: 36 – 44

Table 3.4 Auricular Surface Aging Stages[4]

Age	Description
20 – 24	Billows are well defined, broad, fine-grained and transversely oriented, surface exhibits a granular texture
25 – 29	Slight loss of billowing, and striae are beginning to replace the billows, granulation becomes more coarse, organization is transversely oriented
30 – 34	Billowing is greatly reduced and replaced by striae, some of the transverse organization is lost, the surface exhibits increased granularity compared to the previous phase, and small amounts of microporosity may be present
35 – 39	Striae formation and billowing are reduced, the surface is uniformly granular, transverse organization is greatly reduced, but still present, small amount of microporosity is present, minimal changes in apical activity
40 – 44	Complete absence of billowing, with only small amounts of striae still present, transverse organization is lost, partial granulation of the surface still present, with partial densification (islands), slight amounts of reto-auricular activity
45 – 49	Complete absence of both billows and striae, loss of granulation with replacement by increasing amounts of densification, irregular surface due to densification process, increased retro-auricular activity causes irregularity in the margins, slight changes in the apex occur
50 – 60	Surface irregularity becomes a prominent feature, granulation is minimal or absent, the inferior face is lipped, apical changes are marked, retroauricular activity is moderate, macroporosity is present
60 +	Irregular, nongranular surface, macroporosity may be present, apical activity may be present, margins are likely to be very irregular and lipped, the retroauricular surface may be riddled with osteophytes, no indication of transverse organization, billows, or striae are present

particular feature, and then all three scores of the unknown are summed and compared to scores associated with established age ranges (Iscan et al. 1984: 148 – 156, Steele and Bramblett 1988: 149 - 150). As Iscan et al. (1984: 153 - 155) points out, this technique has a wide age range, and can be used to determine age at death between age 22 and 67. However, there are three problems with the use of this aging technique; the study that this technique employs includes an all-male sample, occupational stress and diseases may accelerate the rate of degeneration of the fourth sternal rib, and only the fourth sternal rib should be used for this aging technique since each of

[4] Source: Lovejoy et al. 1985: 21 - 27

the ribs exhibits different rates of development and degeneration (Steele and Bramblett 1988: 150).

Several techniques analyzing both developmental and degenerative aspects of the vertebrae can be included to determine the approximate age-at-death of an individual. The techniques utilized on the vertebrae are very similar to aging methods for other skeletal regions. For example, vertebrae exhibit an epiphyseal ring that is similar to the epiphyses of the appendicular skeleton, and appears on certain vertebrae at known schedules. Also, the surface of the centra can be analyzed similarly to that of the aging of the pubic symphysis and auricular surface in that vertebrae centra exhibit a distinct morphology at different life cycle stages.

3.2 Vertebral Aging Techniques

The approximate age of a lumbar vertebra can be determined by assessing several factors; including epiphyseal plate closure, degree of epiphyseal ring obliteration, and degeneration. Exact age estimates using the lumbar vertebrae alone are problematic, but an approximate age of the individual vertebra can be determined through careful observations. If the neural arches of the vertebra are separate from the vertebral body without any indication of post-mortem damage, then the vertebra can be aged to approximately ages zero to six years. Complete fusion of the lumbar centrum and the neural arches with the absence of secondary epiphyses would indicate that the vertebra was approximately 7 – 12 years old at death. Individuals between 13 – 24 years are characterized by the presence of secondary epiphyses, with the exception of the vertebral rings (Steele and Bramblett 1988: 132). Between the ages of 24 and 49 years, lumbar vertebrae still exhibit striations, but may also exhibit mild-to-moderate lipping of articular surfaces, mild to moderate macroporosity, and mild obliteration of the secondary epiphyses (Steele and Bramblett 1988: 132 - 133). Vertebrae older than 50 years are characterized by the absence of striations on

the vertebral body, moderate to excessive obliteration of the secondary epiphyses, and the increased presence of other indicators of vertebral degeneration, including osteophytes, lipping, and macroporosity (Steele and Bramblett 1988: 133).

3.3 Hypotheses

The basic premise of this thesis project is to investigate the possibility that certain dimensions of the lumbar vertebrae exhibit statistically significant changes over the course of the lifetime. Half of this experiment is similar to the series of analyses performed by Ericksen (1976: 575 - 580, 1978a: 241- 246, 1978b: 247 - 250), with the exception that race will not be a discriminating factor in results analysis. With this in mind, there is the expectation that the results of this part of the experiment would be consistent with those of Ericksen (1976: 575 - 580, 1978a: 241- 246, 1978b: 247 - 250), but to maintain the integrity of the experiment and omit any bias for one outcome or another, a null hypothesis must first be established. The following is the proposed null hypothesis for this thesis project: H_0^1: No statistically significant relationship exists between the centrum height, inferior transverse centrum diameter, superior transverse centrum diameter, medial transverse centrum diameter, centrum circumference, sex, and age of each lumbar vertebra. In regards to the degree of sexual dimorphism exhibited by the lumbar vertebrae, the following null hypothesis can be postulated: H_0^2: Males and females exhibit no significant differences in vertebral shape or aging.

However, several hypotheses can be constructed if the null hypothesis does not hold. H_1: A statistically significant inverse relationship exists between centrum height and age, which is caused by the phenomenon of lumbar compression throughout the lifespan of an individual. H_2: A statistically significant relationship exists between centrum diameter and age caused by flaring of the vertebral body. H_3: A significant relationship exists between curvature of the vertebral

body and age. H_4: The centra of the lumbar vertebrae exhibit significant differences between males and females. H_5: Males and females exhibit differences in regards to the rate of degeneration of the lumbar region of the spinal column.

4 MATERIALS AND METHODS

4.1 Materials

The purpose of this thesis project is to investigate the link between vertebral height, transverse diameter, and circumference in relation to age and sex to determine if there is a statistically significant change in vertebral shape in relation to age. Data was collected from the William M. Bass Donated Skeletal Collection at the University of Tennessee, Knoxville. A total of 60 individuals, 33 females and 37 males, of ages ranging from 16 to 81 were analyzed from the collection. Figure 4.1 summarizes the demography of the individuals sampled, and Table 4.1 provides specimen numbers for each analyzed specimen. The individuals from the collection were selected based on three criteria: pre-existing data on the individual included known age-at-death and sex, and the presence of intact lumbar vertebrae. Even though known age-at-death was a criterion for inclusion into this study, age was assessed for each individual by analyzing the pubic symphysis and auricular surface, in addition to other age makers. The qualitative analysis of each individual ensured the accuracy of the recorded age-at-death, which was essential to the production of accurate results. Efforts were also made to ensure that the individuals analyzed would exhibit a wide distribution of ages and a relatively equal number of males and females to ensure the efficacy of the results.

Approximately 31 measurements were taken for each individual analyzed. Femoral midshaft diameter was used to assess body mass. For each lumbar vertebra, centrum height, superior transverse diameter, medial transverse diameter, inferior transverse diameter, and the arc of the centrum were measured and recorded. Superior and medial sagittal diameter were also recorded for the first lumbar vertebra for the body mass calculation. Each measurement was

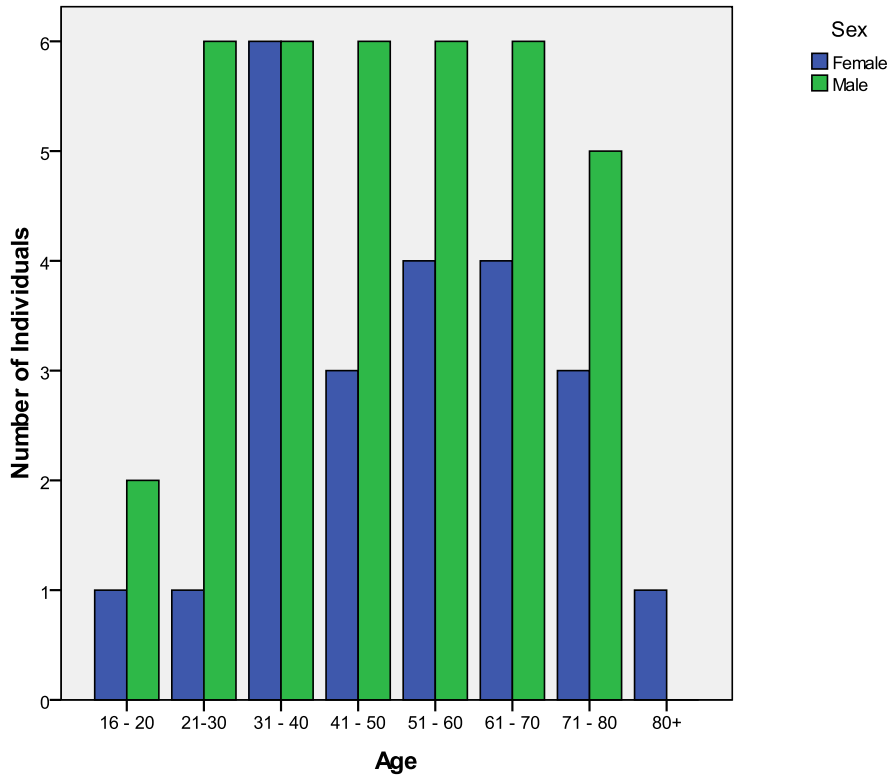

Figure 4.1 Sex and Age Distribution of Individuals Examined

obtained by the direct use of calipers, with the exception of the arc measurement, according to the description provided in Table 4.2. The arc of the centrum was determined by wrapping dental floss around the most medial portion of the centrum and marking the dental floss on the two most lateral portions of the centrum. Afterwards, the length between the two marks, known as the arc of the centrum, was measured using calipers. In addition to the quantitative measurements, qualitative analysis of each individual was conducted in order to confirm the known age-at-death of each individual.

Measurement error was determined in this study by calculating the absolute error for 10 thoracic vertebrae from the skeletal collection at Georgia State University. Centrum height, superior transverse diameter, medial transverse diameter, inferior transverse diameter, and arc

Table 4.1 William M. Bass Donated Skeletal Collection Specimens

Age Range	Sex	Specimen Numbers
16 – 20	M	UT06-04D, UT14-04D
	F	UT15-87D
21 – 30	M	UT34-99D, UT08-89D, UT04-90D, UT21-92D, UT19-90D, UT82-08D
	F	UT78-07D
31 – 40	M	UT65-06D, UT14-93D, UT17-08D, UT29-04D, UT17-00D, UT25-04D
	F	UT07-97D, UT04-81D, UT39-01D, UT41-07D, UT02-86D, UT06-89D
41 – 50	M	UT07-94D, UT09-89D, UT03-90D, UT102-06D, UT01-03D, UT75-06D
	F	UT20-03D, UT35-07D, UT07-01D,
51 – 60	M	UT42-02D, UT11-89D, UT19-94D, UT39-93D, UT12-05D, UT24-05D
	F	UT37-02D UT100-06D UT17-03D UT57-06D
61 – 70	M	UT35-93D UT08-94D UT06-91D UT43-02D UT31-93D UT38-08D
	F	UT02-92D UT112-07D UT05-97D UT06-95D
71 +	M	UT41-06D UT31-02D UT20-07D UT03-02D UT18-93D
	F	UT31-04D UT113-07D UT90-07D UT23-00D

were measured twice for each of these vertebrae, and both measurements were averaged. Absolute error was then calculated for each measurement and converted to a percentage, which is recorded in Table 4.3. Measurement error for this study is relatively low. Measurement error for the circumference measurement, however, is closer to 2%. The circumference measurement likely has a higher percentage error due to the indirect method utilized to obtain the circumference estimates.

Three indices were calculated using the measurements: arc-chord, height-breadth, and flaring (Ericksen 1976: 241 - 244). Arc-chord measurement was obtained by dividing the medial transverse diameter by the arc of the centrum. Height-breadth index can be calculated by dividing the centrum height by the medial transverse diameter, and this index would indicate the

Table 4.2 Description of Measurements

Measurement	Description
Centrum Height	The distance between the most superior and inferior aspects of the centrum in the sagittal plane.
Superior Transverse Diameter	The distance between the two most lateral aspects of the superior extremity of the centrum in the transverse plane.
Medial Transverse Diameter	The distance between the two most lateral aspects of the midpoint of the superior-inferior height of the centrum in the transverse plane.
Inferior Transverse Diameter	The distance between the two most lateral aspects of the inferior extremity of the centrum in the transverse plane.
Arc	The circumference of the centrum measured from the most lateral extremities of the centrum at the midpoint of the superior-inferior height in the transverse plane.

relationship between height and width of the centrum. Flaring index is calculated by dividing the medial transverse diameter of the centrum by the average of the superior and inferior transverse diameters. This index indicates the degree to which each centrum bows inwards.

4.2 Statistical Methods

All of the data were input into SPSS for statistical analysis. Several statistical tests were performed in order to determine if there is a statistically significant relationship between age and centrum shape or size. ANOVA were calculated for each variable by converting age to an age range based on the biological stages of aging described by Steele and Bramblett (1988: 56 - 57). A total of four age categories were created in order to conduct the ANOVA. The first age category comprises individuals between the ages of 16 and 24, and constitutes adolescent individuals (Steele and Bramblett 1988: 56 – 57). The second age category comprises young adults between the ages of 25 – 49. The last two age categories describe early (50 – 64) and late (65+) old adulthood. The ANOVA were performed in such a way as to test the validity of the age grouping based on the selected trait, which would confirm or deny whether or not these age ranges constituted statistically distinct groups.

Table 4.3 Measurement Error Percentage

Height	0.7615%
Superior Transverse Diameter	0.286%
Inferior Transverse Diameter	0.778%
Medial Transverse Diameter	0.459%
Circumference	1.926%

In addition to the ANOVA, correlation coefficients were calculated using all of the lumbar vertebrae to determine the nature of the relationship between the measurements and age. Correlation coefficients show whether the variables in this experiment correlate positively or negatively with one another, and combined with the ANOVA, will reveal how the vertebral body dimensions change as an individual ages.

Multivariate linear regression was also included to determine how well each measurement, compared to one another, is able to predict age. Multivariate linear regression analysis combines all of the variables into x-values that are then included in the following equation to predict age (y-value):

$$y = \alpha + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \ldots. \beta_k x_k$$

In the previous equation, the variable α is the constant, β is the coefficient, and k represents the final measurement analyzed. The subscripts for each β and x-value represent which measurement analyzed corresponded to that particular coefficient and x-value combination. As the equation demonstrates, each of the measurements were analyzed together for each linear regression, and each coefficient displayed a corresponding beta weight, which is a numeric estimate of how much that measurement contributed to predicting age. The larger the beta weight, regardless of being negative or positive, the more that measurement contributed to predicting age. In this experiment, beta weights alone were analyzed in order to determine which

measurements contributed the most to predicting age, and consequently had a stronger relationship with age compared to the other variables.

Independent samples t-tests were conducted in order to determine if the means of each group were statistically distinct from one another. Also, principal components analyses were performed on the data set in order to determine how individuals are distributed across factor axes and which traits contribute to the separation. In addition to using the raw data to perform the principal components analysis, ratios for each trait were calculated by summing all traits together, specifically centrum height, superior, inferior, and medial transverse diameters, and arc, followed by the division of each original variable by the summary variable. PCAs were then performed on these scaled traits.

Each of these tests were performed using all of the available data at first, and then cases were selected based on vertebra number (L1, L2, L3, L4 or L5), and sex to determine if the validity of the age categories may be based on either of these factors. Additionally, three of the samples exhibited L6 vertebrae, of which were included in the L5 cases instead of grouping them as a separate category.

5 RESULTS

The primary objective of this paper is to determine the relationship between age and vertebral shape, and to determine what, if any, role that sex plays in regards to vertebral aging. Additionally, the possibility that the lumbar vertebrae differ significantly based on sex is explored. Whether variation between the sexes can explain the variation found within the data set is also investigated.

5.1 Correlations

A correlation matrix is used in this study to determine if any correlations exist among the measurements, indices, biological age, sex, and body size. Femoral midshaft diameter, abbreviated FMD, is used as a proxy for estimating body size. Table 5.1 summarizes the correlations observed among the variables analyzed in the sample. Several variables correlate significantly with one another. Superior transverse diameter (STD) correlates significantly and strongly with both medial transverse diameter (MTD) and inferior transverse diameter (IFD). Additionally, medial transverse diameter correlates strongly with inferior transverse diameter. Height shows a significant correlation with superior, inferior, and medial transverse diameters, as well as the arc measurement, though these correlations were relatively weak, corresponding to Pearson correlations from 0.289 to 0.370. The arc measurement also exhibits weak but statistically significant correlations with height, superior, inferior, and medial transverse diameters, with Pearson correlations ranging from 0.289 to 0.451. The arc-chord (A-C) index exhibits significant correlations with each of the centrum diameter measurements and arc, though these correlations are only moderately strong, ranging from -0.526 to 0.645. Height-breadth (H-B) index exhibits a significant negative correlation with centrum height, all the transverse diameters, arc and arc-chord, the strongest of which is the correlation with medial transverse

Table 5.1 Correlation Coefficients

	Pearson	Height	STD	ITD	MTD	Arc	A-C	H-B	Flaring	Age	Age Range	Sex	FMD
Height	Correlation	1	.370**	.353**	.359**	.289**	.105	.152**	.067	-.083	-.003	.465**	.243**
	Significance		.000	.000	.000	.000	.068	.008	.250	.152	.960	.000	.000
STD	Correlation	.370**	1	.866**	.895**	.356**	.502**	-.740**	.100	.142**	.213**	.433**	.545**
	Signficance	.000		.000	.000	.000	.000	.000	.083	.007	.000	.000	.000
ITD	Correlation	.353**	.866**	1	.784**	.451**	.324**	-.651**	-.103	.212**	.281**	.488**	.604**
	Signficance	.000	.000		.000	.000	.000	.000	.074	.000	.000	.000	.000
MTD	Correlation	.359**	.895**	.784**	1	.299**	.645**	-.856**	.495**	.043	.110*	.440**	.485**
	Significance	.000	.000	.000		.000	.000	.000	.000	.417	.037	.000	.000
Arc	Correlation	.289**	.356**	.451**	.299**	1	-.526**	-.180**	-.123*	.065	.144*	.372**	.447**
	Significance	.000	.000	.000	.000		.000	.002	.034	.263	.013	.000	.000
A-C	Correlation	.105	.502**	.324**	.645**	-.526**	1	-.607**	.543**	-.017	-.018	.101	.077
	Significance	.068	.000	.000	.000	.000		.000	.000	.768	.755	.080	.193
H-B	Correlation	.152**	-.740**	-.651**	-.856**	-.180**	-.607**	1	-.470**	-.104	-.131*	-.225**	-.423**
	Signficance	.008	.000	.000	.000	.002	.000		.000	.071	.023	.000	.000
Flaring	Correlation	.067	.100	-.103	.495**	-.123*	.543**	-.470**	1	-.242**	-.242**	.032	-.066
	Signficiance	.250	.083	.074	.000	.034	.000	.000		.000	.000	.584	.270
Age	Correlation	-.083	.142**	.212**	.043	.065	-.017	-.104	-.242**	1	.944**	-.126*	.274**
	Significance	.152	.007	.000	.417	.263	.768	.071	.000		.000	.017	.000
Age Range	Correlation	-.003	.213**	.281**	.110*	.144*	-.018	-.131*	-.242**	.944**	1	-.057	.282**
	Significance	.960	.000	.000	.037	.013	.755	.023	.000	.000		.281	.000
Sex	Correlation	.465**	.433**	.488**	.440**	.372**	.101	-.225**	.032	-.126*	-.057	1	.473**
	Significance	.000	.000	.000	.000	.000	.080	.000	.584	.017	.281		.000
FMD	Correlation	.243**	.545**	.604**	.485**	.447**	.077	-.423**	-.066	.274**	.282**	.473**	1
	Significance	.000	.000	.000	.000	.000	.193	.000	.270	.000	.000	.000+	

diameter with a Pearson correlation of -0.856, followed closely by the superior transverse diameter with a correlation coefficient of -0.740

Raw age and biological age range shows significant correlations with superior and inferior transverse diameters, though biological age range also exhibits a significant correlation

with arc. Sex correlates significantly with height, superior, inferior, and medial transverse diameters, as well as arc and height-breadth index. Femoral midshaft diameter correlates significantly with all measurements with the exception of arc-chord and flaring indices. The significance of the correlations between these variables indicates that there likely exists a statistically significant relationship between these demographic markers and several dimensions of the vertebrae.

5.2 ANOVA

ANOVA and linear regression analysis are included to determine if vertebral shape is significantly different based on biological age range. Table 5.2 summarizes the results of the ANOVA tests analyzing all of the vertebrae, then each vertebrae number individually (L1, L2, L3, L4, and L5 &L6). L5 and L6 are grouped together considering only three samples out of 60 individuals exhibited L6 vertebrae.

ANOVA of all of the vertebrae collectively reveal that several of the measurements are significantly different when comparing age categories. Superior, inferior, and medial transverse diameters are found to exhibit a significant relationship with age, though medial transverse diameter appears to have a weaker relationship with age in comparison to the other two diameter measurements. Height-breadth and flaring indices also exhibit a statistically significant relationship with biological age categories, and vertebral flaring appears to be more strongly related to biological age than height-breadth index.

When each lumbar number is analyzed individually through ANOVA, many fewer significant relationships were found with each measurement. L1 and L4 exhibit no significant relationship with any variable, which indicates that L1 and L4 vertebrae of different age

Table 5.2 ANOVA Using Biological Age Range

Variable	All Vertebrae		L1		L2		L3		L4		L5	
	F	Sig.	F	Sig.	F	Sig.	F	Sig.	F	Sig.	F	Sig.
Height	.807	.491	.255	.857	.566	.639	.874	.460	.662	.579	.079	.971
STD	**6.212**	**.000**	1.225	.309	1.481	.230	1.949	.132	2.207	.097	2.223	.095
ITD	**7.288**	**.000**	1.512	.221	**2.879**	**.044**	1.866	.146	.895	.450	2.534	.066
MTD	**2.860**	**.037**	.894	.450	.846	.475	.760	.521	.757	.523	1.807	.156
Arc	1.976	.118	.458	.713	.075	.973	1.355	.266	1.291	.286	.531	.663
A-C	.489	.690	.700	.556	.786	.507	2.290	.088	1.138	.342	.583	.629
H-B	**2.973**	**.032**	.606	.614	.569	.638	1.418	.247	1.422	.246	1.405	.251
Flaring	**6.363**	**.000**	1.636	.191	1.854	.148	**4.338**	**.008**	2.128	.107	**3.527**	**.020**

categories cannot be distinguished based on any of these measurements or indices. L2 vertebrae only exhibit a significant relationship when analyzing inferior transverse diameter (IFD). L3 exhibits a significant relationship with flaring index, as well as the L5 & L6 grouping. However, neither L3 nor L5 & L6 exhibits a significant relationship with any other variable. Though the ANOVA alone reveals the significance of the relationship between age and vertebral dimensions, more thorough analyses are needed to uncover exactly which age categories are being distinguished by age. In order to understand fully the relationship between these variables and age, post-hoc tests are analyzed in order to determine which age categories are statistically distinct from one another.

The results of the post-hoc tests based on the ANOVA that includes all of the lumbar vertebrae are summarized in Table 5.3. Only the significant relationships are included in the table. L2, despite exhibiting a significant relationship with inferior transverse diameter (IFD), did not exhibit any significant relationships between the age groups in the post-hoc tests, and therefore L2 post hoc tests are not included in Table 5.3. When analyzing all of the vertebrae, the youngest age range (16 – 24 years) can be distinguished from the two older age ranges (50 – 64,

Table 5.3 ANOVA Post-hoc Results

Measurement	Groups Compared	All Vertebrae	L3 only	L5 & L6 only
STD	1 – 3	0.001		
	1 – 4	0.001		
ITD	1 – 4	0.000		
	1 – 3	0.004		
	2 – 4	0.021		
MTD	1 – 3	0.034		
H-B	1 – 4	0.022		
Flaring	1 – 4		0.032	
	2 – 4	0.000	0.010	0.030
	3 – 4			0.035

and 65 + years) when STD, ITD, MTD, H-B and flaring are considered. Additionally, the second age category (25 – 49 years) can be distinguished from the oldest group (65 + years) when analyzing IFD and flaring. Flaring also distinguishes the two older groups, which are ages 50 – 64, and 65 +. When analyzing L3 only, age group one (16 – 24 years) and age group two (25 – 49 years) are statistically different from group four (65 + years) with respect to flaring. The L5 & L6 analysis shows that, in regards to flaring, age groups two and three are significantly different from one another.

The next set of ANOVA includes only males, and then includes only females in order to determine if there are any sex differences in regards to aging patterns. The results from ANOVA using only males are summarized in Table 5.4.

When all of the different lumbar vertebrae elements are included, males only exhibit a significant relationship between age and flaring index. However, when each individual lumbar number is analyzed, several more significant relationships are found between age range and the various measurements. L1, which exhibits no significant relationship with age when including both males and females, does exhibit several significant relationships with age and superior (STD), inferior (ITD), and medial (MTD) transverse diameters, as well as arc, height- breadth

Table 5.4 ANOVA (Males Only)

Variable	All Vertebrae		L1 only		L2 only		L3 only		L4 only		L5 & L6 only	
	F	Sig.	F	Sig.	F	Sig.	F	Sig.	F	Sig.	F	Sig.
Height	.079	.971	.141	.935	.235	.872	.211	.888	.415	.743	.441	.726
STD	2.223	.095	**8.751**	**.000**	**3.074**	**.041**	**3.995**	**.016**	**3.312**	**.032**	**3.117**	**.039**
ITD	2.534	.066	**10.13**	**.000**	2.421	.083	**6.413**	**.002**	**4.235**	**.012**	1.358	.273
MTD	1.807	.156	**7.225**	**.000**	2.275	.098	2.443	.082	2.659	.064	2.128	.115
Arc	.531	.663	**2.990**	**.032**	.776	.516	.289	.833	1.338	.279	1.970	.138
A-C	.583	.629	.850	.468	.840	.482	1.193	.328	**3.672**	**.022**	1.100	.363
H-B	1.405	.251	**8.274**	**.000**	1.438	.249	2.381	.087	**3.609**	**.023**	2.680	.063
Flaring	**3.527**	**.020**	**6.599**	**.000**	**1.272**	**.300**	1.391	.263	**2.886**	**.050**	2.549	.073

index, and flaring index. All of these relationships, with the exception of arc, exhibit an F-value of over 6.0, indicating that the relationship with age is strong. When analyzing L2 of males, only superior transverse diameter (STD) and flaring index exhibit significant relationships with biological age range. Excluding all lumbar elements except L3 in the male portion of the sample reveals that superior and inferior transverse diameters exhibit a significant relationship with biological age range, with inferior transverse diameter exhibiting a stronger relationship with biological age than superior transverse diameter. When excluding all samples but the L4 vertebra of the males in the sample, STD, ITD, and each of the indices are found to exhibit significant relationships with biological age. L5 & L6 vertebrae alone exhibit only one significant relationship that was between biological age range and STD. The post-hoc tests from these ANOVA reveal which age categories are distinct from one another in regard to the analyzed measurements.

Table 5.5 summarizes the results of the post-hoc tests for the ANOVA restricted to males within the sample. When using all of the lumbar elements for the ANOVA, groups two and three could be significantly distinguished from group four in regards to flaring, which is the reason for the significant relationship between flaring and age in the male-only sample. By

Table 5.5 ANOVA Post-hoc Results (Males Only)

Measurement	Groups Compared	All Vertebrae	L1 only	L2 only	L3 only	L4 only	L5 & L6 only
STD	1 – 2		0.007				
	1 – 3		0.000	0.033	0.014	0.022	0.026
	1 – 4		0.001				
ITD	1 – 2		0.013				
	1 – 3		0.000		0.002	0.007	
	1 – 4		0.000		0.016		
	2 - 3		0.025		0.045		
MTD	1 – 2		0.001				
	1 – 3		0.000			0.047	
	1 – 4		0.045				
Arc	1 – 2		0.020				
A-C	3 – 4					0.015	
H-B	1 – 2		0.000				
	1 – 3		0.000			0.014	
	1 – 4		0.019				
Flaring	2 – 4	0.030	0.000			0.046	
	3 – 4	0.035					

analyzing the first lumbar element, group one could be distinguished from groups two, three, and four on the basis of STD, ITD, MTD, and H-B. Group two could be distinguished significantly from group three on the basis of ITD, and group three could be distinguished from group four on the basis of A-C when analyzing the L1 of males. When analyzing the L1 of males, groups two and three exhibit distinct, significant differences from group four on the basis of flaring index. The arc measurement is also significantly different between only groups one and two when analyzing the L1 of males. When analyzing the L2 of males, only groups one and three exhibit significant differences in regards to STD. The analysis of the L3 of males reveals that the first biological age group could be distinguished from the third biological age group when analyzing STD and ITD. Also, on the basis of ITD, the first biological age group exhibits significant

differences from the fourth age group, and the second age group exhibits significant differences from the third group. The L4 of males are significantly different between age groups one and three in regards to STD, ITD, MTD, and H-B. Groups three and four are different in the L4 of males on the basis of A-C, and groups two and four are different on the basis of flaring. The L5 and L6 of the male sample only exhibit significant differences between the first and third age groups.

When females are analyzed separately from the rest of the sample, several significant relationships are found that differ from those of the male-only analyses. The results of these ANOVA are found in table 5.6. Unlike the males, females exhibit several significant relationships with age. Height, STD, ITD, arc and H-B are all significantly related to biological age in females. When analyzing the L1 element alone, or the L2 element alone, females only exhibit a significant relationship with flaring index, which is in sharp contrast to various significant relationships found when analyzing the L1 of males. The L3 elements of females significant differ based on biological age categories when analyzing centrum height and H-B index. The L4 elements of females distinguish different age categories significantly in regards to arc, and L5 & L6 elements only distinguish age categories when analyzing the superior and inferior transverse diameters.

The post-hoc tests for these ANOVA restricted to females are summarized in Table 5.7. When all of the vertebral elements are included in the sample, females exhibit significant differences in height between the first age group and the second and third age groups. Height is also significantly different between the two older age groups. STD and ITD are significantly different between the first two age groups and the oldest age group. Arc measurement is also significantly different between the second and fourth age group, and H-B index is significantly

Table 5.6 ANOVA (Females Only)

Variable	All Vertebrae		L1 only		L2 only		L3 only		L4 only		L5 & L6 only	
	F	Sig.	F	Sig.	F	Sig.	F	Sig.	F	Sig.	F	Sig.
Height	**9.858**	**.000**	2.692	.075	4.004	0.023	**3.658**	**.031**	1.531	.239	1.052	.390
STD	**5.568**	**.001**	1.510	.244	0.976	0.425	3.101	.051	2.633	.080	**8.140**	**.001**
ITD	**6.950**	**.000**	1.331	.294	1.773	0.186	2.565	.085	2.050	.141	**3.222**	**.043**
MTD	2.157	.097	1.407	.272	0.491	0.693	1.610	.220	2.841	.065	2.509	.087
Arc	**5.495**	**.001**	.528	.668	0.980	0.423	1.501	.246	**3.697**	**.030**	1.882	.164
A-C	.199	.897	.616	.613	0.446	0.723	.326	.807	1.276	.311	.670	.580
H-B	**4.338**	**.006**	2.904	.062	2.689	0.076	**3.519**	**.035**	2.417	.098	1.934	.155
Flaring	1.827	.146	**3.593**	**.033**	**1.093**	**0.376**	1.608	.221	.522	.672	.933	.442

different between group two or three and group four. When analyzing the L2 of females only, height of the centrum is significantly different in group one and group three. Height and height-breadth index are also able to distinguish age groups when analyzing the L3 of females, specifically between groups three and four for both measurements, and groups two and four for H-B only. The circumference of the L4 of females only differs significantly between groups two and four. And finally, STD is significantly different between the first two age groups and the fourth age group, as well as the first age group and third age group. In order to further confirm the results of these ANOVA, linear regressions are utilized to determine the significance of the relationship between the biological age categories and the various measurements.

5.3 Regression Analysis

In order to directly compare the results of this thesis to Ericksen's research (1976: 575 - 580, 1978a: 241 - 246, 1978b: 247 - 250), multiple linear regressions are analyzed using the measurements and indices that are also used in the ANOVA. The multiple linear regressions mirror that of the ANOVA in that the first set of analyses did not exclude any lumbar elements, and the subsequent analyses include only one element per analysis. Also, this process is repeated for both males only and females only to determine if there are any

Table 5.7 ANOVA Post-hoc Results (Females Only)

Measurement	Groups Compared	All Vertebrae	L2 only	L3 only	L4 only	L5 & L6 only
Height	1 – 2	0.003				
	1 – 3	0.000	0.024			
	3 – 4	0.001		0.043		
STD	1 – 3					0.043
	1 – 4	0.007				0.003
	2 – 4	0.007				0.004
ITD	1 – 4	0.002				
	2 - 4	0.001				
Arc	2 – 4	0.001			0.018	
H-B	2 – 4	0.011		0.049		
	3 – 4	0.016		0.044		

differences in vertebral aging among the sexes. The following results focus on the beta weights of each multivariate linear regression, which is essentially a measure of the strength of the variable in regards to predicting age.

Table 5.8 summarizes the results of the multivariate linear regression analyzing both males and females. The beta weights for each regression are listed, and none of the regressions are statistically significant ($p < 0.05$). When analyzing all of the vertebral elements, flaring index appears to predict age better than any of the other variables, with ITD having the lowest beta weight and, consequently, exhibiting a low correlation with age. Among the L1 vertebrae, MTD is able to predict age better than the other variables. However, H-B**,** ITD, Arc, A-C, and flaring also exhibit a strong ability to predict age among the L2 vertebrae. Flaring, ITD, and MTD exhibit a strong relationship with age when analyzing the L3 and L4 vertebrae. STD also exhibits a strong ability to predict age among the L3 vertebrae. When analyzing the L5 and L6 vertebrae, MTD, Arc, A-C, and H-B are all strong predictors of age.

Males exhibit a similar pattern of the strength of these variables in predicting age. When analyzing all of the male lumbar elements, MTD, arc, A-C, and H-B exhibit the highest beta weights for the linear regressions, and therefore these values are able to predict age better than

Table 5.8 Beta Weights for Multivariate Linear Regression Using Males and Females

Variable	All Vertebrae	L1 only	L2 only	L3 only	L4 only	L5 & L6 only
Height	-.033	.584	-.458	-.361	-.260	.512
STD	.062	.410	.802	-3.026	-.990	-.391
ITD	.008	.500	1.629	-2.320	-1.561	-.574
MTD	.223	**-1.567**	.175	**4.772**	**3.225**	1.942
Arc	-.242	-.038	**-1.822**	.802	-.869	**-2.288**
A-C	-.268	.228	-1.376	.607	-.668	-1.745
H-B	-.226	-.688	.697	-.022	-.151	-1.051
Flaring	**-.346**	.207	1.181	-2.530	-1.693	-.968

all of the other variables. Similar to using both males and females in the sample, MTD exhibits the strongest ability to predict age among the L1 vertebrae. Also similar to the test that includes males and females, the L2 vertebrae of males exhibits the strongest beta weights for arc, A-C, and flaring. However, among the L2 vertebrae of males, MTD instead of ITD exhibits the strongest ability to predict age. For both the L3 and L4 vertebrae, MTD exhibits the strongest ability to predict age compared to the other variables. Also, STD and ITD exhibit a stronger ability to predict age among the L3 vertebrae compared to that of the L4 vertebrae. Flaring index, unlike the sample that included both males and females, is the strongest predictor for age among the L5 and L6 vertebrae of males. Overall, among the males, MTD is the strongest predictor for each element individually, though when coalesced together, H-B exhibits the strongest ability to predict age.

For the females alone using all of the vertebral elements, MTD is the strongest predictor of age, followed closely by H-B and flaring index. For the L1 vertebrae, H-B is the strongest predictor of age, which is in contrast to the male and female sample, and the male sample alone, both of which reveal that MTD is the strongest predictor of age. H-B is also the strongest predictor of age among the L2 elements of females. The L3 and L4 elements, similar to the other linear regression results, exhibit very similar beta weights to one another. For both elements,

Table 5.9 Beta Weights for Multivariate Linear Regression Using Males Only

Variable	All Vertebrae	L1 only	L2 only	L3 only	L4 only	L5 & L6 only
Height	.241	.516	.100	-.473	-.711	1.149
STD	.217	.874	-.394	-3.198	-1.348	-2.610
ITD	.188	.912	-.167	-3.034	-1.697	-2.129
MTD	-.343	**-2.001**	**3.887**	**5.591**	**4.961**	**4.937**
Arc	-.425	-.084	-2.940	1.409	-1.459	-2.674
A-C	-.444	.469	-2.080	1.254	-1.094	-2.074
H-B	**-.590**	-.428	.083	.254	.820	-1.956
Flaring	-.162	.751	-1.194	-3.621	-2.480	-3.139

MTD is the strongest predictor of age, and the variables STD, ITD, and flaring all exhibit similarly strong beta weights. For the L5 and L6 of females, the arc measurement is the strongest predictor of age, and both MTD and A-C exhibits high beta weights, which indicate that they are also strong predictors of age. Over all, MTD, flaring and H-B appear to be strong predictors of age among females.

5.4 T-Tests

The results of the t-tests reveal several significant differences between males and females, specifically in regards to height, inferior transverse diameter, and medial transverse diameter (Table 5.11). When analyzing all of the vertebrae together, males and females differ significantly in height, ITD and arc. ITD and MTD are significantly different between males and females when analyzing the L1 or L2 vertebrae independently. Additionally, MTD of the L3 or L4 vertebra is significantly different between males and females. Among the L5 & L6 vertebrae, males and females only differ significantly in regards to centrum height. Each of these significant relationships exhibits relatively high F-values, which range from 4.622 to 9.795. The significant relationships for the L2 vertebral elements exhibits the weakest relationships compared to the rest of the relationships, corresponding to 4.622 for ITD and 4.739 for MTD.

Table 5.10 Beta Weights for Multivariate Linear Regression Using Females Only

Variable	All Vertebrae	L1 only	L2 only	L3 only	L4 only	L5 & L6 only
Height	-.635	-2.361	-5.496	-1.538	-.049	.529
STD	-.719	.790	1.684	-5.751	-6.948	.736
ITD	-.465	.910	2.554	-4.233	-6.264	-.910
MTD	**2.542**	1.660	2.653	**8.158**	**9.246**	1.433
Arc	.644	-.264	.716	2.868	2.323	**-2.323**
A-C	.790	-.075	.593	2.113	1.908	-2.235
H-B	1.316	**3.327**	**6.927**	2.050	.099	-.947
Flaring	-1.153	.769	2.259	-4.598	-6.634	-.663

The arc measurement for all of the vertebrae exhibits the strongest significant difference between males and females, with an F-value of 9.795.

5.5 Principal Components Analysis

Like the t-tests, PCAs are included to determine if the majority of variation in the sample could be explained analyzing sex, and to show whether males and females differ in regards to centrum shape. Two PCAs are performed using the data collected; the first utilizes the raw data for each grouping, and the second includes ratios that are calculated by adding all of the measurements together, and dividing the individual measurements by the sum. The second PCAs that utilize ratios instead of the raw data eliminated size from the test, which often accounts for the majority of the variation in the sample.

The first PCA (PCA #1) uses the raw data from all of the lumbar vertebra measurements. The first axis (factor 1) extracted exhibits relatively high and positive component loadings, which ranged from 0.542 – 0.936, and accounted for 62.6% of the variation in the sample. The second axis (factor 2) differentiates between height and arc, and places both of these measurements on the positive side of the axis, while all diameter measurements are placed on the negative side of the axis. The second axis (factor 2) accounts for 17.269% of the variation in the sample. Figures 5.1 and 5.2 summarize the results of the first PCA. Figure 5.1 explains the

Table 5.11 T-Test Results

Variable	All Vertebrae		L1 only		L2 only		L3 only		L4 only		L5 & L6 only	
	F	Sig.	F	Sig.	F	Sig.	F	Sig.	F	Sig.	F	Sig.
Height	**5.025**	**.026**	1.828	.182	.230	.634	.237	.628	.072	.790	**8.750**	**.004**
STD	1.121	.291	1.593	.212	1.168	.284	1.789	.186	1.445	.234	1.731	.193
ITD	**5.802**	**.017**	**5.211**	**.026**	**4.622**	**.036**	2.602	.112	1.431	.237	.033	.856
MTD	2.039	.154	**7.440**	**.008**	**4.739**	**.034**	**5.251**	**.026**	**6.026**	**.017**	.405	.527
Arc	**9.795**	**.002**	.932	.338	.630	.431	3.621	.062	2.787	.100	.410	.525
A-C	.096	.757	1.665	.202	.439	.510	3.129	.082	3.346	.072	.121	.729
H-B	.055	.814	3.951	.052	1.444	.234	.241	.625	.325	.571	.013	.908
Flaring	.524	.470	.852	.360	.979	.327	3.242	.077	**5.541**	**.022**	2.628	.110

variation on the x-axis, which corresponds to the first extracted axis. Size is likely accounts for the first axis of this PCA. However, females generally tend to fall on the negative portion of the x-axis, and males tend to fall on the positive side of the axis, which indicates that the two sexes are distinctly different based on size, and that sex may also compose some of the variation on the first axis. Figure 5.2 highlights the role that shape, or lumbar element, plays with regards to the variation in the sample. L1 through L5 are separated in a gradient on the y-axis of the graph, which likely points to shape accounting for the second extracted axis in this PCA. However, the lumbar elements also change dramatically in size when moving cranially to caudally, so the second extracted axis may also be influenced by the size of the lumbar elements.

Size is eliminated as a factor in the second PCA (PCA #2) by using ratios instead of raw data. The results of the second PCA are very similar to the first one, except the axes are switched. The first axis (factor 1) extracted composes 55.407% of the variation in the sample, and the second axis (factor 2) accounts for 20.242% of the variation in the sample. The first component extracted, much like the second component extracted from PCA #1, separates the height and arc measurements from the diameter measurements. The element type appears to

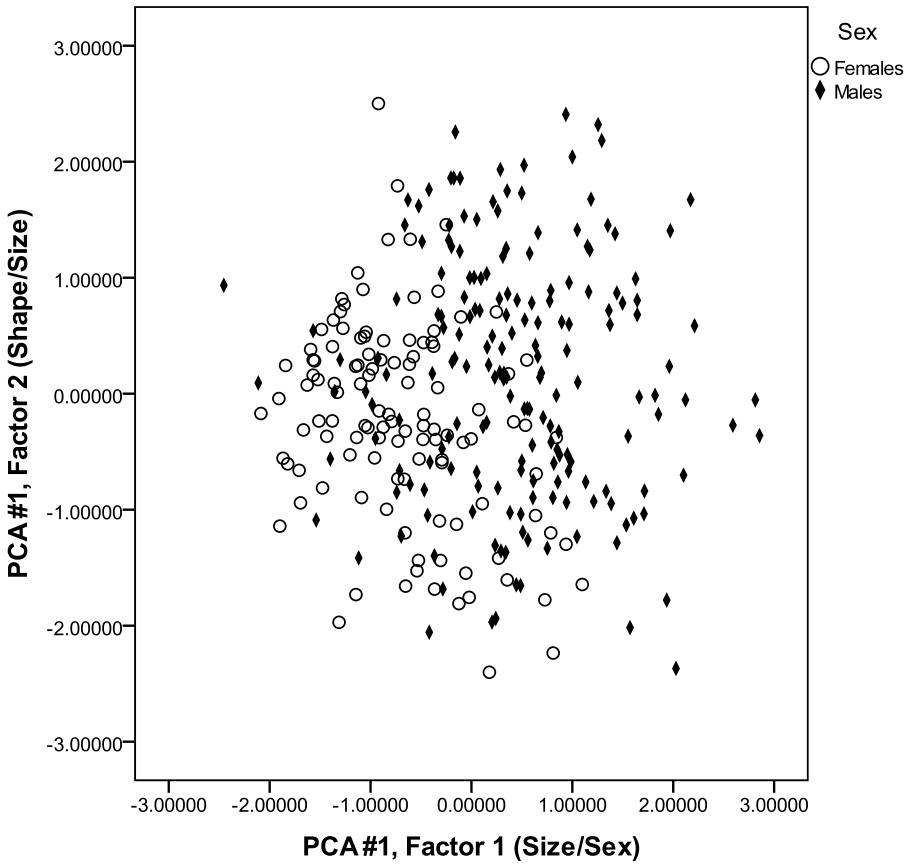

Figure 5.1 PCA #1 Result (by Sex)

account for the first axis extracted considering that the lumbar elements are clearly distinguished on the axis that corresponds with this variable when the results of this PCA are graphed (Figure 5.3). The second axis extracted from PCA #2 separates the sample based on the medial transverse diameter and the arc measurement, though what exactly is being separated on this axis is much less clear than the first axis. After analyzing which variables the axis is correlated with in the sample (Table 5.12), the second axis is likely separating vertebra based on shape. The second axis is significantly correlated with height-breadth index, arc-chord, and flaring, all of which are expressions of vertebral shape. Age is also significantly correlated, but the correlation is much weaker than that of H-B, A-C, and flaring. Additionally, all of the raw measurements are

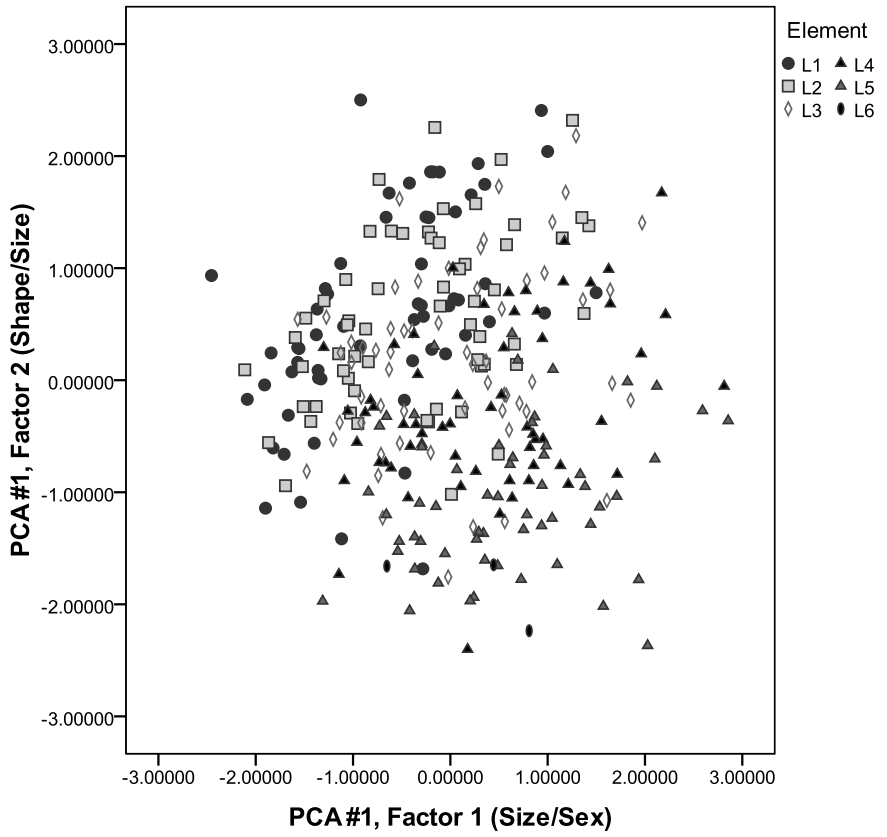

Figure 5.2 PCA #1 Result (by Element)

significantly correlated with the second axis of PCA #2, which corroborates the likelihood that this axis is differentiating vertebrae based on their shape.

The rest of the correlation matrix also yields extremely valuable information about each of the variables in the PCA. Sex and femoral midshaft diameter (FMD) are only significant for the first axis of PCA #1, which separates samples based on sex. The significant correlation with both of these variables confirms that sex is likely what is separating the variables, considering that femoral midshaft diameter is a proxy for size, and that males are, on average, larger than females. The first factor is also significantly correlated to height, STD, ITD, MTD, arc and age range, which seems to indicate that these variables are related to sex differences. Height, arc, H-B, and A-C are all significantly correlated with the second factor of PCA #1, which

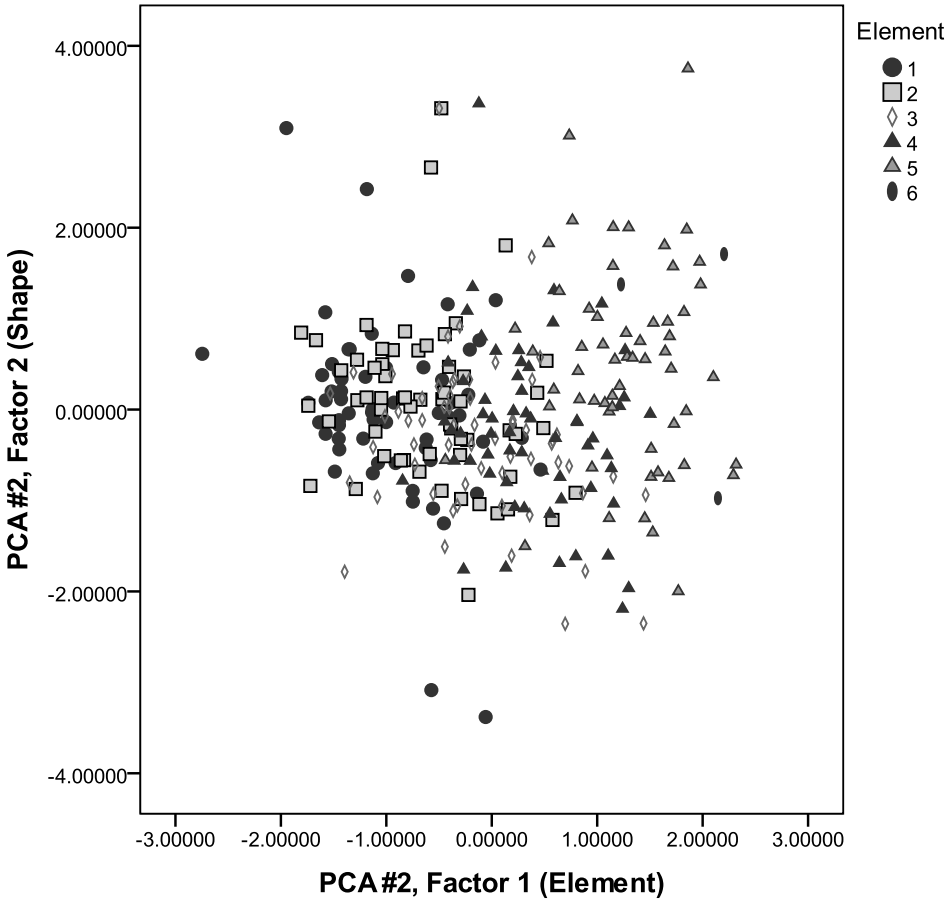

Figure 5.3 PCA #2 (by Element)

corresponded to size. The first factor of PCA #2, which corresponded to lumbar element, correlates significantly with all of the diameter measurements, A-C, H-B, and FMD, which may indicate that the diameter of the centrum and size of the individual correlate with the type of vertebral element.

Table 5.12 PCA Correlation Coefficients

		Height	STD	ITD	MTD	Arc	Age	Age Range	A-C	H-B	Flaring	Sex	FMD
PCA#1	Correlation	**.493****	**.924****	**.896****	**.892****	**.725****	.188	**.256***	.006	**-.490****	-.239	**.570****	**.611****
1st extraction	Significance	**.000**	**.000**	**.000**	**.000**	**.000**	.147	**.046**	.966	**.000**	.063	**.000**	**.000**
PCA #1	Correlation	**.712****	-.012	.042	-.016	**.304***	-.159	-.144	**-.408****	**.533****	-.073	.222	.035
2nd extraction	Significance	**.000**	.925	.745	.905	**.017**	.221	.267	**.001**	**.000**	.576	.086	.795
PCA #2	Correlation	.112	**.599****	**.417****	**.481****	-.190	.211	.247	**.744****	**-.395****	-.138	.248	**.390****
1st extraction	Significance	.389	**.000**	**.001**	**.000**	.142	.102	.055	**.000**	**.002**	.288	.054	**.003**
PCA #2	Correlation	**.391****	**-.376****	**-.713****	**-.370****	**-.738****	**-.293***	**-.293***	**.562****	**.626****	**.404****	-.123	-.238
2nd extraction	Significance	**.002**	**.003**	**.000**	**.003**	**.000**	**.022**	**.022**	**.000**	**.000**	**.001**	.345	.075

6 DISCUSSION

6.1 Aging and the Lumbar Vertebrae

Based on the results of the ANOVA, the vertebrae of humans do exhibit specific changes in centrum dimension that create distinct groups based on biological age. Additionally, males and females do exhibit several differences in regards to which dimension of the centrum create are significantly different with age. When analyzing the height of the vertebrae, only females are found to exhibit a significant relationship between age and vertebral height. Considering the compressive forces that are found on the lumbar segments of the vertebral column throughout the human lifecycle, this result is somewhat surprising. Females appear to exhibit a negative correlation with vertebral height and age, meaning that as an individual ages, the height of the vertebrae progressively decreases, which is in congruence with the current literature (Ericksen 1976: 575). The L3 of females, unlike the rest of the individual lumbar elements, also exhibit a significant relationship with age and vertebral height, specifically between the two older age groups (50 – 64 and 64 + years). This relationship may be explained by the occurrence of lumbar lordosis in pregnant females, which has been known to cause other changes in vertebral body shape known as wedging (Whitcome et al. 2007: 1076). The third lumbar vertebrae, in many cases, may be the apex of the lordotic spine, which would increase the pressure on that specific element. This extra pressure during the lifetime of an individual may increase the degeneration of the L3 of women, especially during old age.

The transverse diameters of each lumbar element do appear to increase as an individual ages, specifically when analyzing both males and females, and females alone. Though the individual lumbar vertebrae of males exhibit several significant relationship**s** between age and the transverse diameter measurements, when analyzing all of the vertebrae together, females

appear to have these dimensions increase throughout their lifetime more consistently than the males, with the exception of medial transverse diameter. Males, however, do appear to exhibit a stronger aging signal compared to females, which may be due to men generally exhibiting a higher center of gravity because more weight is concentrated in the upper body. Another explanation is that occupational stressors, such as frequently lifting heavy objects, may also contribute to this difference between males and females. Additionally, males and females collectively, and females alone, exhibit a significant relationship between age and height-breadth index. Considering both the results for the height and transverse diameters of vertebral bodies, the significance of height-breadth index indicates that the height of the centrum decreases while the diameter of the centrum increases throughout the lifecycle, especially in women.

The results from the flaring index from the ANOVA are surprising considering the rest of the analyses. Males alone exhibit a significant relationship between age range and flaring index, despite the lack of any significant relationships between any of the transverse diameter measurements. In males, especially for the L1, L2, and L4 vertebrae, flaring appears to significantly increase with age, and there are very distinct differences between the young adult age group (25 – 49 years) and the oldest age group (65 + years). This indicates that vertebral flaring becomes increasingly prevalent in males over the age of 65.

Arc and A-C appears to also exhibit a relationship with aging. The L4 element of females and the L1 element of males were the only vertebrae to exhibit a significant relationship between arc and age, and the L4 for males exhibits a significant relationship between A-C and age. Based on this information, and the correlation matrix, it appears that for female L4 and male L1 elements, the circumference of the vertebral bodies increases throughout the human lifecycle, and the curvature index for the L4 of males decreases as an individual ages.

The results of the multivariate linear regression analysis, however, seems to indicate that medial transverse diameter, especially in males, is the best predictor of age compared to the other measurements. In females, medial transverse diameter is the best predictor of age for L3 and L4, but for L1 and L2 vertebrae, height-breadth index is the better predictor of age. This result is interesting because the ANOVA indicated that medial transverse diameter does not significantly change with age in men, with the exception of L1, and MTD exhibited no significant relationship with age among women when analyzing any lumbar element. H-B is also not significant in the ANOVA for females.

6.2 Current Literature Comparisons

The general growth trajectories of both height-breadth index and flaring index from this study are not consistent with that of Ericksen's (1976: 575). According to Ericksen, height-breadth index decreases with age, whereas flaring index relatively increases with age, though these results do exhibit some variability when examining different vertebral elements (Ericksen 1976: 578). In this study, however, when analyzing all of the vertebral elements together, height-breadth index and flaring index both exhibit negative correlations with age. This discrepancy may be due to a difference between the methods used by Ericksen and in this experiment; Ericksen (1978b: 274) excluded osteophytes when measuring the transverse diameters of her samples, whereas osteophytes are included when measuring the samples in this study. Not excluding the osteophytes in this study likely increased the average of the superior and inferior transverse diameters, making the rate at which the medial transverse diameter increases appear much slower than that of the other diameter measurements.

Ericksen (1978a: 241 – 246) concludes that height-breadth index for the L1 and L2 vertebral elements all exhibited negative, significant correlation with age, with the exception of

the L1 of white females. She also states that flaring index exhibits a positive correlation with age, though none of the samples she analyzed exhibited a significant relationship between age and flaring index. However, according to the results of this study, height-breadth and flaring index both exhibit negative correlations with age, and the L1 of males exhibits a significant correlation between age and both flaring and height-breadth indices. Additionally, the L2 of males and the first two lumbar elements of females all exhibit a significant correlation between age and flaring index. Flaring index appears to be a better predictor of age than height breadth index for males, whereas the opposite is true for females.

When examining the L3 and L4 vertebral elements, Ericksen (1976: 578 -579) concludes that both men and women exhibit a statistically significant relationship between age and height-breadth index, and that flaring is both statistically not significant and generally did not decrease or increase with age. However, the results of the ANOVA and multivariate linear regression analyses from this experiment are not consistent with the conclusions of Ericksen. L3 and L4 in males and females both exhibit relatively high beta weights for flaring index, and relatively low beta weights for height-breadth index, indicating that flaring index is the better predictor of age. Also, only the L3 in females and the L4 in males have a significant relationship between age range and height-breadth index, not all of the elements for both males and females according to Ericksen (1976: 578 – 579). Also, the L4 of males exhibits a significant relationship between age range and flaring index, whereas none of the groups in Ericksen's sample exhibited a significant relationship with age and flaring index.

In Ericksen's (1978b: 247) final study of the L5 element, height-breadth index exhibited a significant, but low correlation with age for both males and females. Flaring index, similar to the other lumbar elements, exhibited a positive, non-significant correlation with age (Ericksen

1978b: 247). The L5 and L6 elements of this study, however, did not exhibit a significant correlation with either flaring or height-breadth index in males or females, and their relative ability to predict age was the same as the L1 and L2 elements in this study.

There are several major differences between the research performed in this study and the research performed by Ericksen (1976: 575, 1978a: 241, 1978b: 247) that may be able to explain the discrepancies between the results of each experiment. First, Ericksen (1978a: 241) used linear regression analysis to determine which of the indices that she used exhibited significant relationships with age, whereas in this study, ANOVA analysis is used to determine the significance of the relationship between age range and each measurement or index. The major difference between using a linear regression model compared to an ANOVA analysis is that linear regression models are asking whether a given variable, y, can be predicted using a known variable, x. ANOVA analysis instead does not ask whether x can predict y, but instead tests the viability of pre-determined groups by comparing the variation within the groups from the variation outside of the groups. In other words, Ericksen was testing whether or not a given index (x) could predict age (y), whereas the ANOVA analysis was testing whether or not the biological age groups constituted real groups given the various vertebral dimensions. Also, in order to properly perform the linear regression modeling in her experiment, Ericksen did not divide the ages into groups like in this experiment because the raw age of each individual sampled would be needed in order to make the linear regression model viable. Much like Ericksen (1978b: 241), this study did separate samples based on sex, but Ericksen also separated her samples based on race, which is not the case in this experiment. Also, Ericksen's sample size was approximately 337 individuals, which is much larger than the sample size of this study.

Rühli et al. (2005: 466) reported in their experiment, which analyzed a modern and historic population, that males of the modern population exhibit a significant correlation with age in regards to the medial transverse diameter of the L1 and L5, whereas the females exhibit no significant correlations with any dimension measured. The only inconsistency with their results is that the L5 of males in this experiment did not exhibit a significant relationship with age. However, Rühli et al. (2005: 467) employed multiple linear regression analysis instead of ANOVA to determine if these dimensions exhibit a relationship with age, which may explain the discrepancy between their results and the results of this experiment.

6.3 Sex Differences

The results of the t-tests indicate that males and females do differ significantly in regards to several dimensions, specifically centrum height, inferior transverse diameter, and arc. Several of the individual vertebral elements also exhibit some statistically significant differences between males and females. Medial transverse diameter appears in several individual elements to be noticeably different between males and females, with the exception of the L5 & L6 elements. Inferior transverse diameter also distinguishes males and females in the L1 and L2 elements. Though only a handful of measurements from the t-tests were significantly different for males and females, the results of the PCA analysis lends more support for the theory that the lumbar region of the spine does exhibit sexual dimorphism.

The first axis of PCA #1 appears to separate the sample based on size, but also clearly separates the sample based on sex. Females comprise most of the negative portion of the axis, and males appear to be polarized towards the positive end of the axis, indicating that the difference between males and females comprises approximately 62.5% of the variation in the sample. Considering that the first factor for the PCA also distinguishes the vertebral bodies based

on size, the clear grouping of males and females along this axis also indicates that size is likely the largest factor that distinguishes male from female lumbar elements. This hypothesis is consistent with the results of the t-test, in which primarily raw measurements of the vertebral bodies, as opposed to indices, were significantly different between males and females.

6.4 Limitations

Within the context of this experiment, there were several limitations to this study that may have affected the results. First, the sample size analyzed is relatively small compared to other studies (Ericksen 1976: 575, Rühli et al. 2005: 460). Considering only 60 individuals total were analyzed, the results of tests that separate the sample based on sex may be skewed since the sample size for each individual sex would range from about 25 – 35 individuals. Also, the results of this experiment only hold true for individuals ranging from the age of 16 – 80, since, due to time and availability of resources, individuals outside of this range could not be analyzed.

7 CONCLUSIONS

The purpose of this study was to determine if the dimensions of the vertebral bodies showed significant differences as an individual aged, as well as to determine if the lumbar segment of the vertebral column was significantly different between males and females. After analyzing the results of each experimental method, it is clear that, within the context of this study, the vertebral bodies do exhibit significant changes in shape with age. The height of the vertebral bodies does decrease with age, as the transverse diameters of the vertebral bodies increase with age. When including osteophytes in the measurements of the superior and inferior transverse diameters, these diameters expand faster than the rate at which the medial transverse diameter expands. Indices, such as height-breadth and flaring, do exhibit some significant correlations with age, though these correlations differ based on the sex of the individual.

This study also shows that males and females exhibit different significant changes in vertebral shape with age, and, in general, do exhibit sexual dimorphism in the lumbar segment of the spinal column. For females, height-breadth index appears to be a better predictor of age for individual lumbar elements compared to flaring index, and the opposite is true for males. The majority of the variation in the sample is due to the size of each element, which is linked closely with the sex of the individual.

Further research can yield more information about the nature of the relationship between age and vertebral dimensions, as well as the sexual dimorphism exhibited by the lumbar elements. Comparison of the anterior and posterior centrum heights could yield more information about the phenomenon of wedging found in females, and whether this significantly changes with the age of an individual (Whitcome et al 2007: 1076 - 1078). Also, analysis of the

sagittal dimensions of centrum body could determine whether the progressive extension of the vertebral body occurs in the sagittal plane as well as the transverse plane.

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